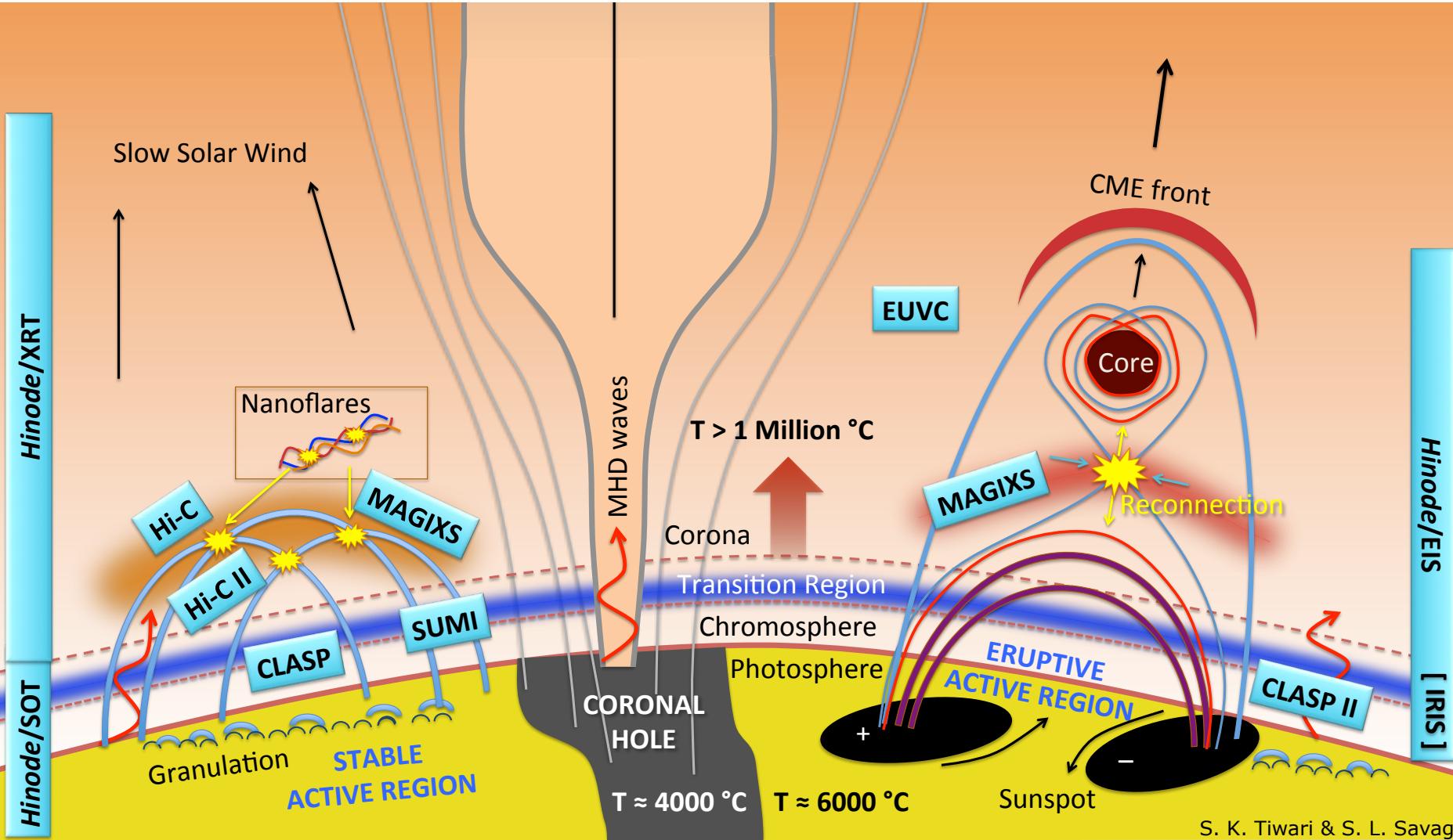


Advancing Knowledge of the Coronal Heating Problem using the Sounding Rocket Platform

Dr. Amy Winebarger

NASA Marshall Space Flight Center

Sounding Rocket Instruments at MSFC



Major Science Goals

BOX 10.1 SOLAR AND HELIOSPHERIC PHYSICS PANEL'S MAJOR SCIENCE GOALS AND ASSOCIATED ACTIONS

SHP1. Determine how the Sun generates the quasi-cyclical variable magnetic field that extends throughout the heliosphere.

- a. Measure and model the near-surface polar mass flows and magnetic fields that seed variations in the solar cycle.
- b. Measure and model the deep mass flows in the convection zone and tachocline that are believed to drive the solar dynamo.
- c. Determine the role of small-scale magnetic fields in driving global-scale irradiance variability and activity in the solar atmosphere.

SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.

- a. Determine whether chromospheric dynamics is the origin of heat and mass fluxes into the corona and solar wind.
- b. Determine how magnetic free energy is transmitted from the photosphere to the corona.
- c. Discover how the thermal structure of the closed-field corona is determined.
- d. Discover the origin of the solar wind's dynamics and structure.

Sounding Rocket Instruments at MSFC

Hi-C I (J. Cirtain, PI)

Flew from WSMR on July 11, 2012

FLOWN
FUNDED
PROPOSED

Hi-C II (J. Cirtain, PI)

Will be launched July, 2016

CLASP I (A. Winebarger, PI)

Launched from WSMR on September 3, 2015

CLASP II (J. Cirtain, PI)

Proposed to launch Spring, 2018

MaGIXS (A. Winebarger, PI)

Will be launched in 2018-19

Goal for this talk –

- Scientific motivation for all instruments
- Give first results from flights
- Describe sub-orbital camera development at MSFC

Sounding Rocket Instruments at MSFC

✓ **Hi-C I** (J. Cirtain, PI)
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MaGIXS (A. Winebarger, PI)
Will be launched in 2018-19

Why the chromosphere?

Why now?

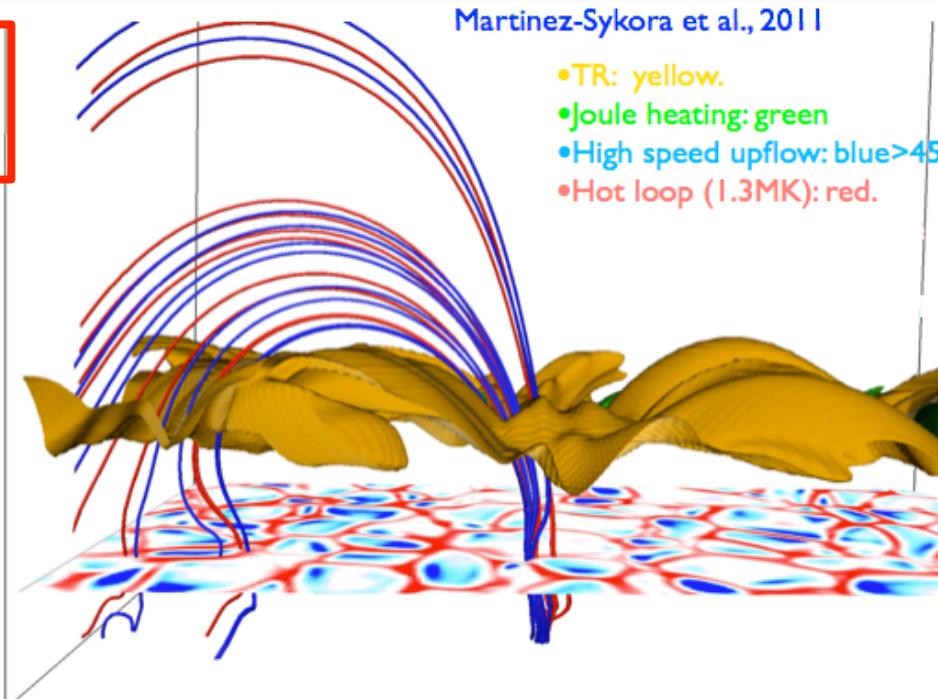
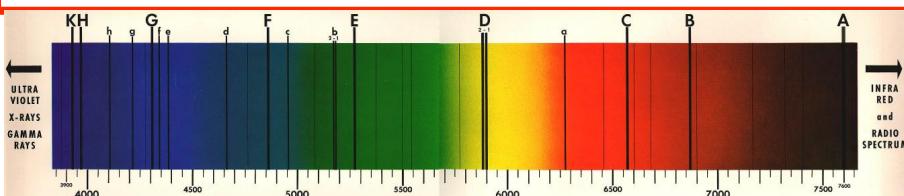
SHP2. Determine how the Sun's magnetism creates its dynamic atmosphere.

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- Discover the origin of the solar wind's dynamics and structure.

Solar and Space Physics: A Science for a Technological Society, 2013

Advances in theoretical modeling of the chromosphere and transition region allow for prediction and interpretation of the results.

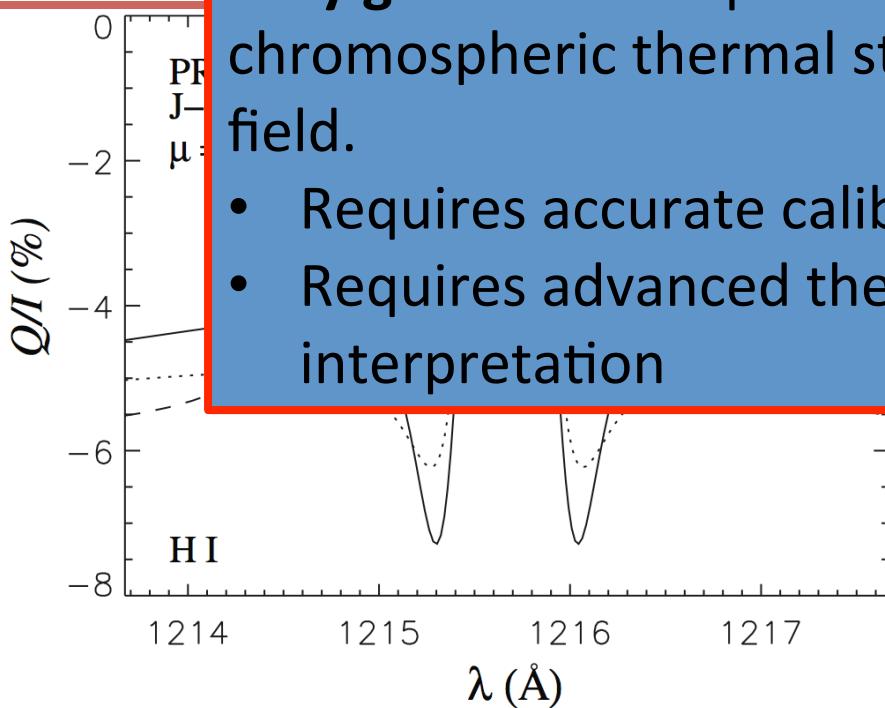
Magnetically sensitive spectral lines formed in chromosphere are not in the visible wavelength range, so measurements have to go above atmosphere.



Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

Science Goal 1: Detect scattering polarization in the wings of Lyman-alpha.

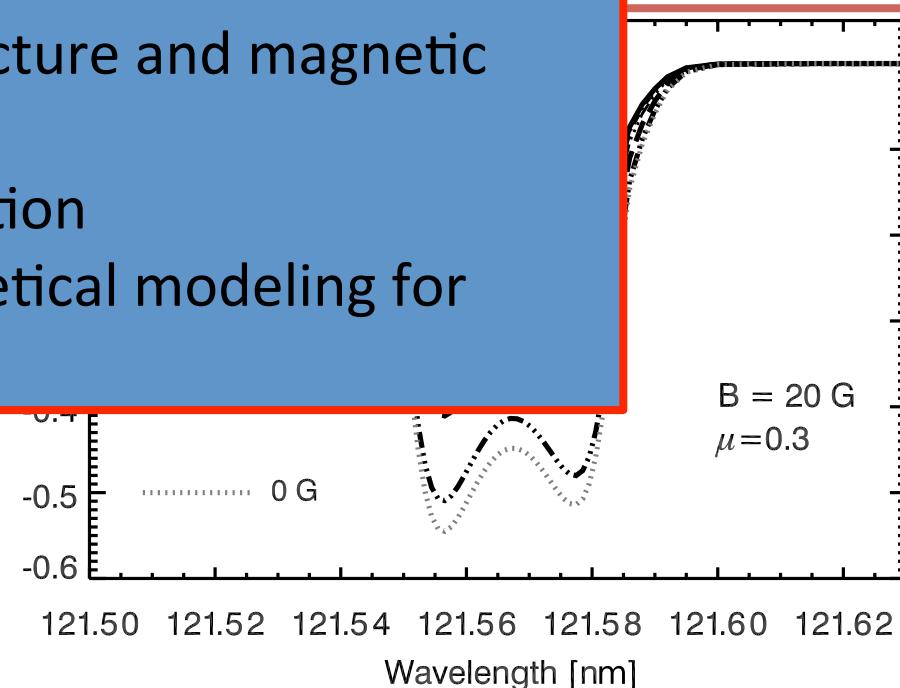
- Sensitive to the thermal structure of the chromosphere.
- Not sensitive to magnetic field.
- Magnitu



Belluzzi et al. 2012

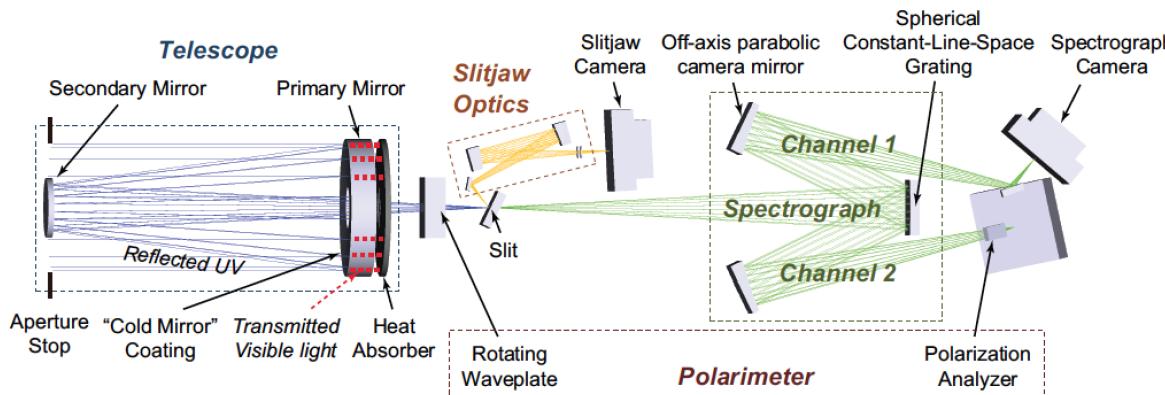
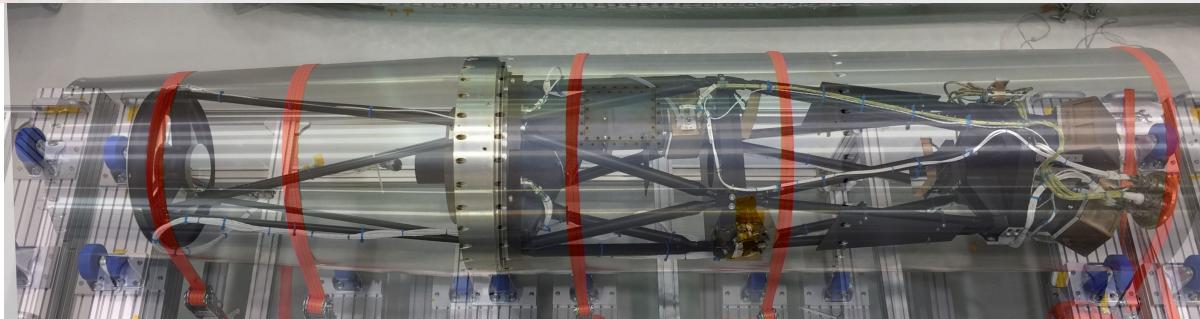
Science Goal 2: Detect polarization in the line core.

- Modified by the magnetic field through Hanle effect
- Magnitude of the polarization is $\sim 0.1\%$
- Accuracy required technological advances in detector systems



Trujillo Bueno et al. 2011

Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)



CLASP is a dual channel spectropolarimeter to measure the polarization of Lyman-alpha.

CLASP was designed and built through an international partnership. Scientists from 11 organizations and 6 countries form the CLASP team. Primary teams and responsibilities are listed below.

MSFC/USA (PI: A. Winebarger) – Cameras, avionics, project management, coordination w/ NASA launch team

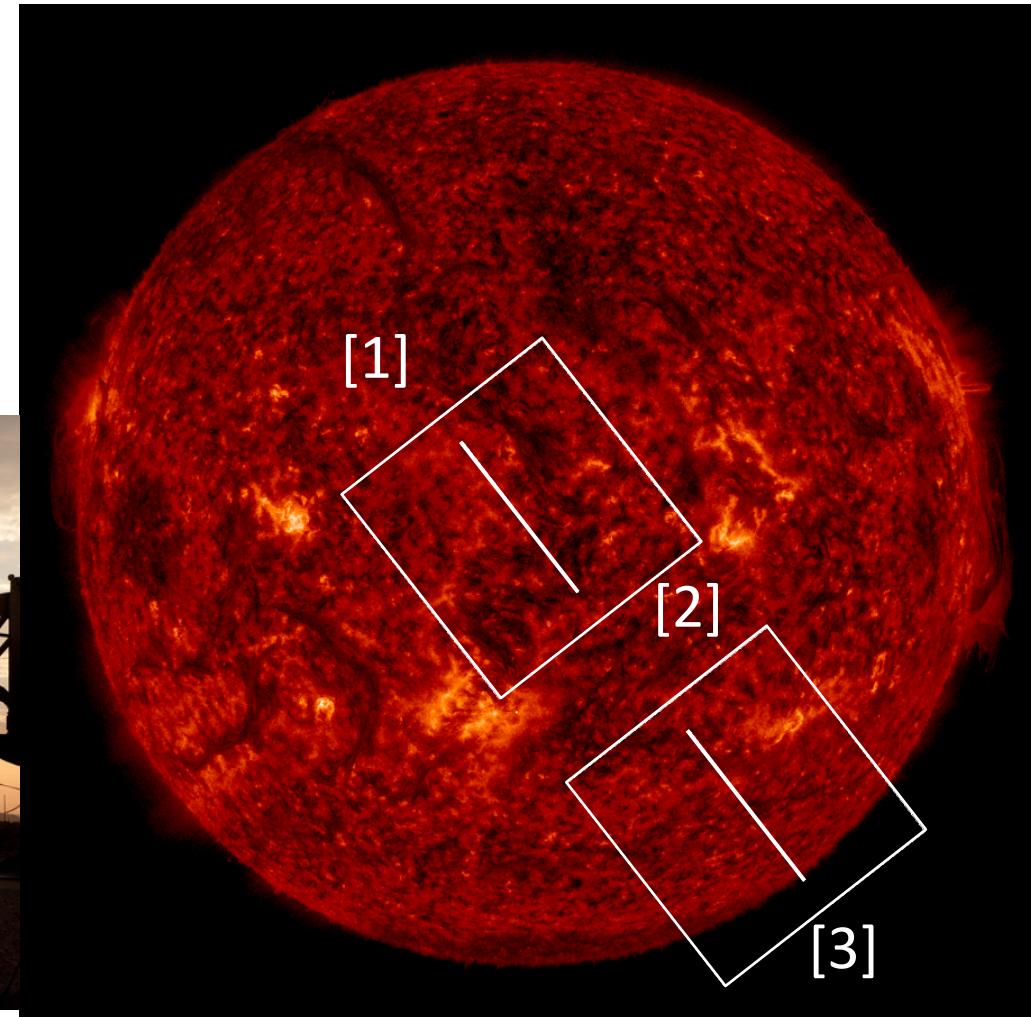
IAS/France (Co-PI: F. Auchère) – Diffraction Grating

NAOJ & JAXA/Japan (Co-PI: R. Kano) – Optics & opto-mechanics, instrument structure

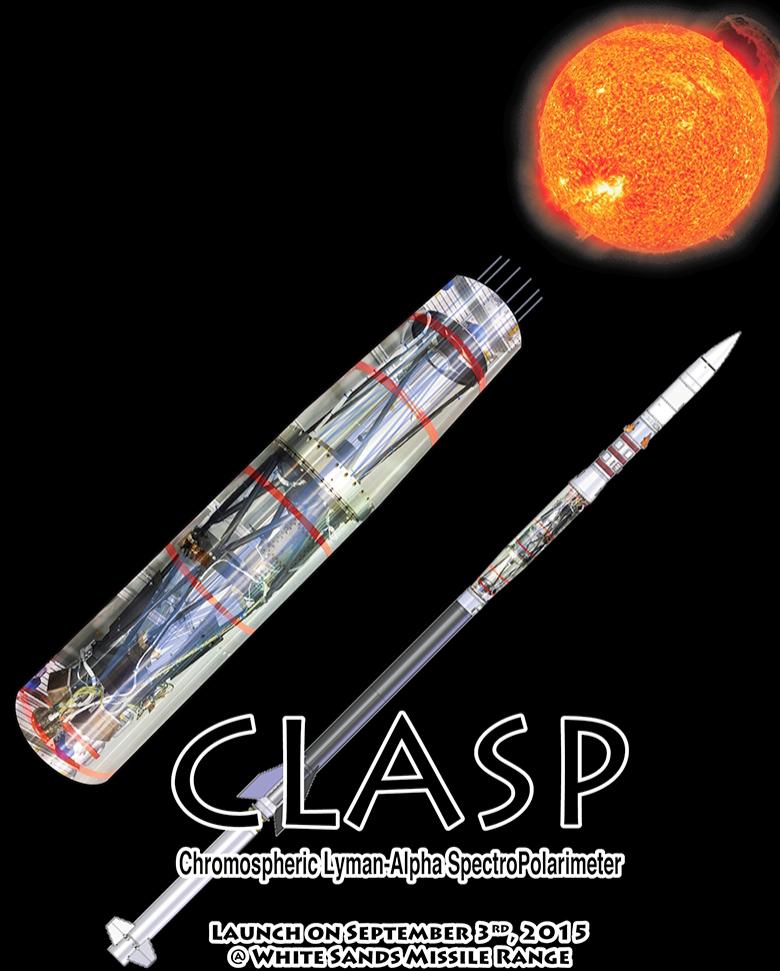
IAC/Spain (Co-PI: J. Trujillo Bueno) – Theoretical predictions and modeling of the Hanle effect

Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

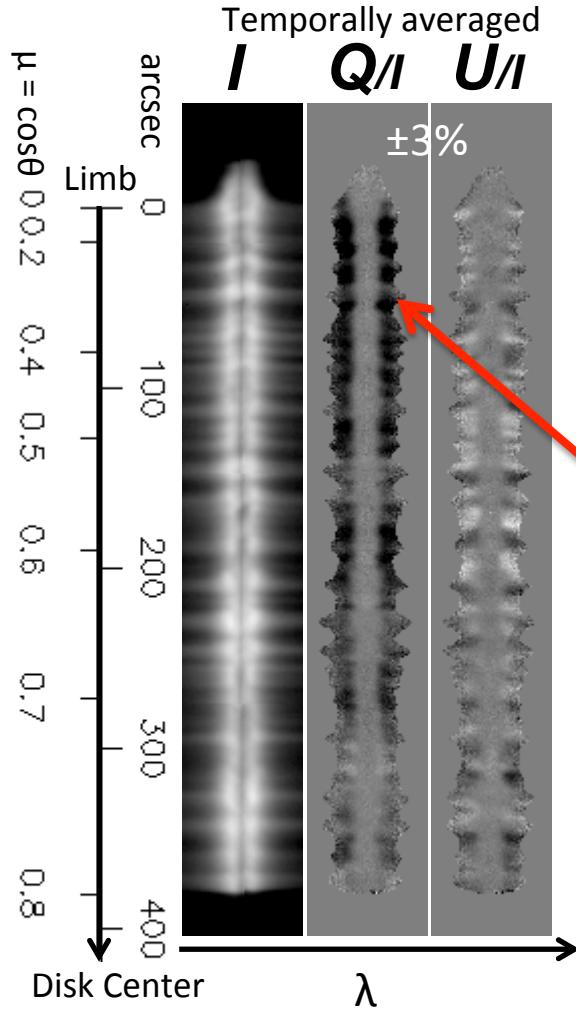
CLASP was launched on September 3, 2015 from White Sand Missile Range



Chromospheric Lyman-Alpha Spectropolarimeter (CLASP)

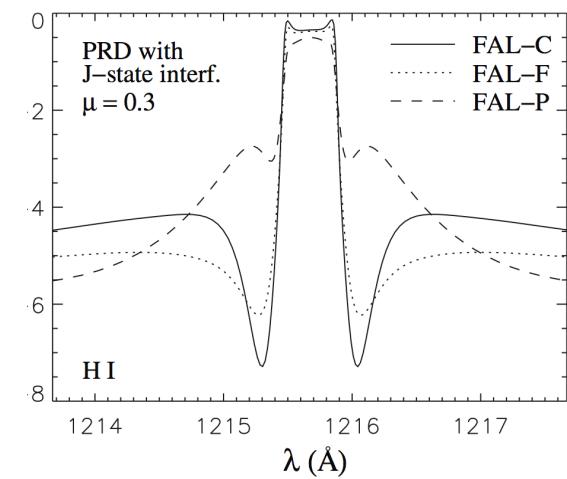
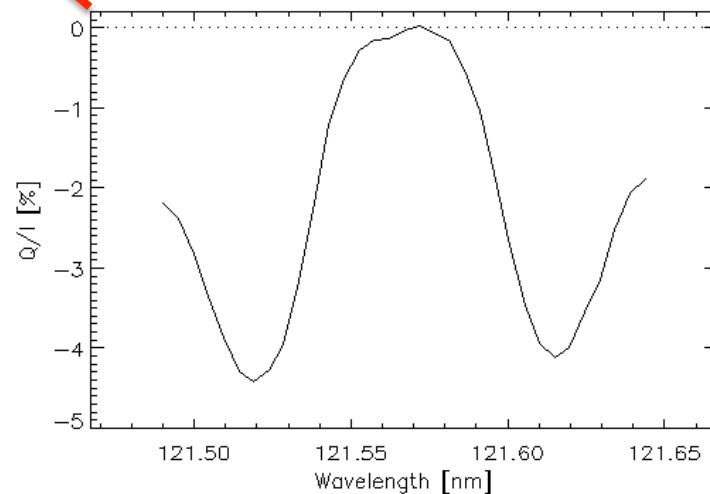


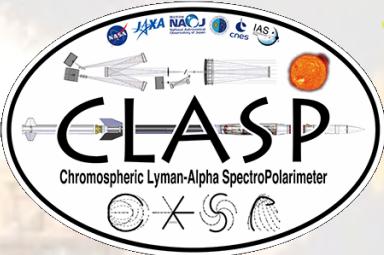
CLASP Initial Results



Further calibrations/investigations are required, but ...

- A few % of polarization in the wing, and a few of 0.1 % in the core.
- A clear **C-to-L variation** in the wing of Q/I.
- Small-scale structures along the slit.
- Q/I profile is essentially **consistent with the model prediction**.

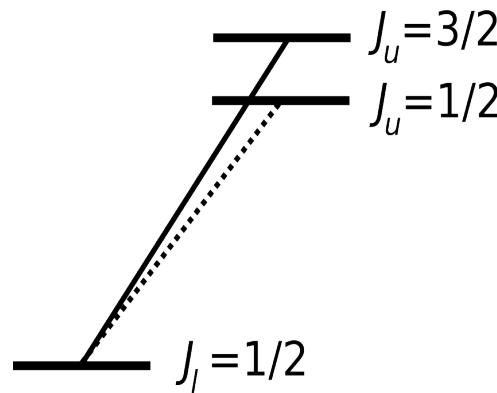
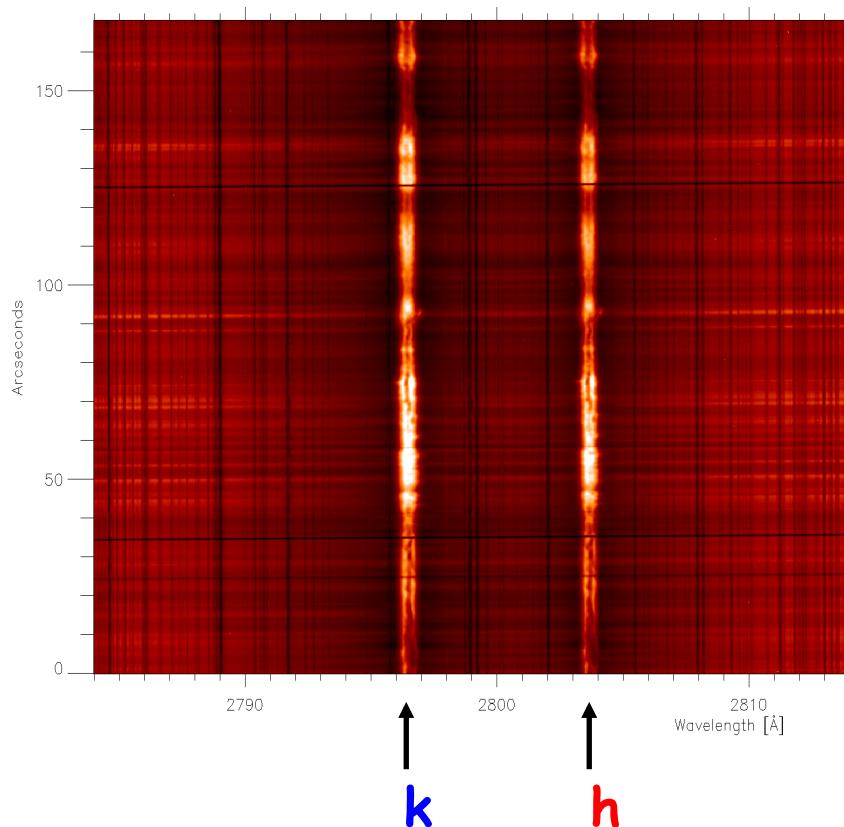




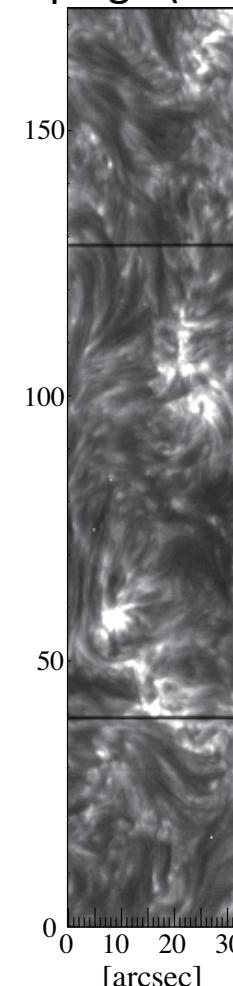
2

What is next for CLASP?

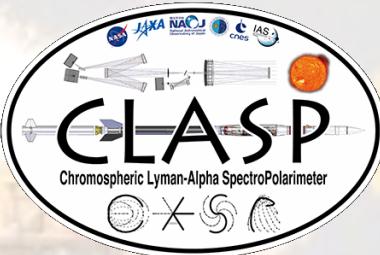
CLASP 2 proposes to change the wavelength to Mg II h&k, another set of magnetically sensitive spectral lines in the UV at ~ 280 nm.



Observing target: QS and plage (if available)



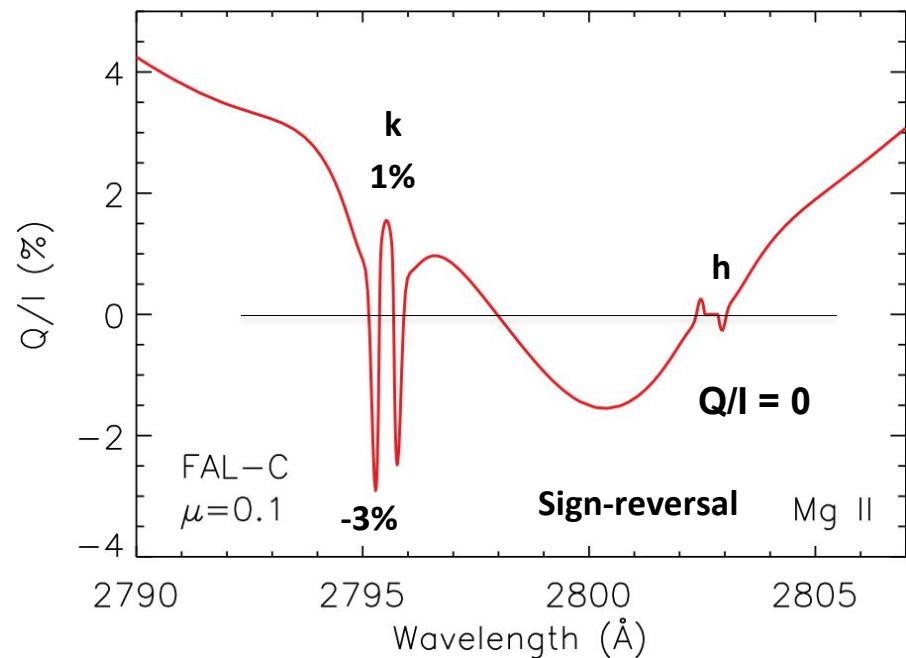
Mg II h & k line core image obtained by IRIS



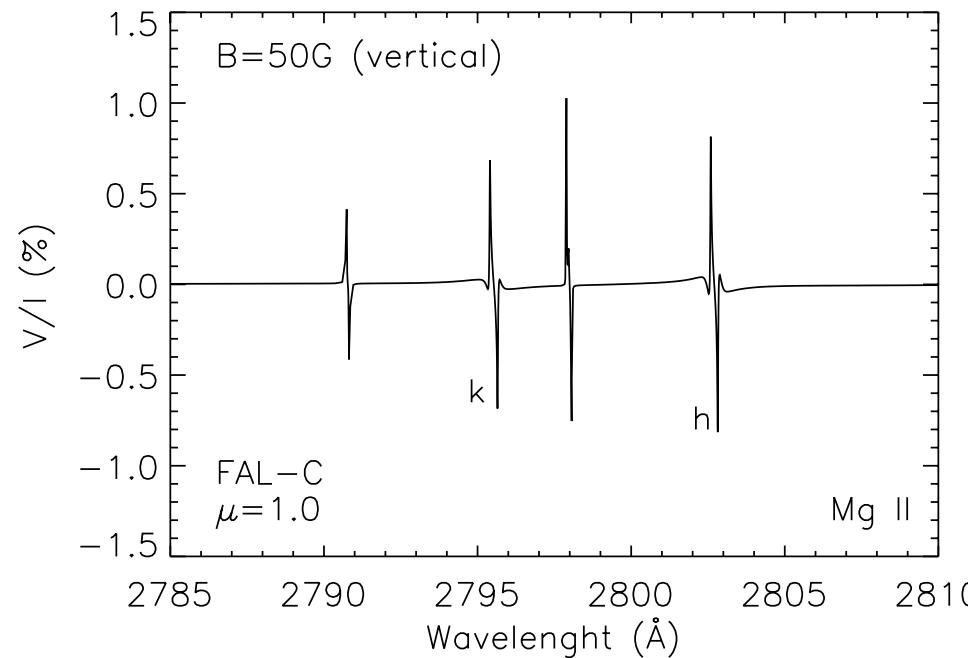
2

What is next for CLASP?

Linear polarization sensitive to scattering polarization and Hanle effect from 5-50 G.



Circular polarization sensitive to Zeeman effect for $B > 50$ G.

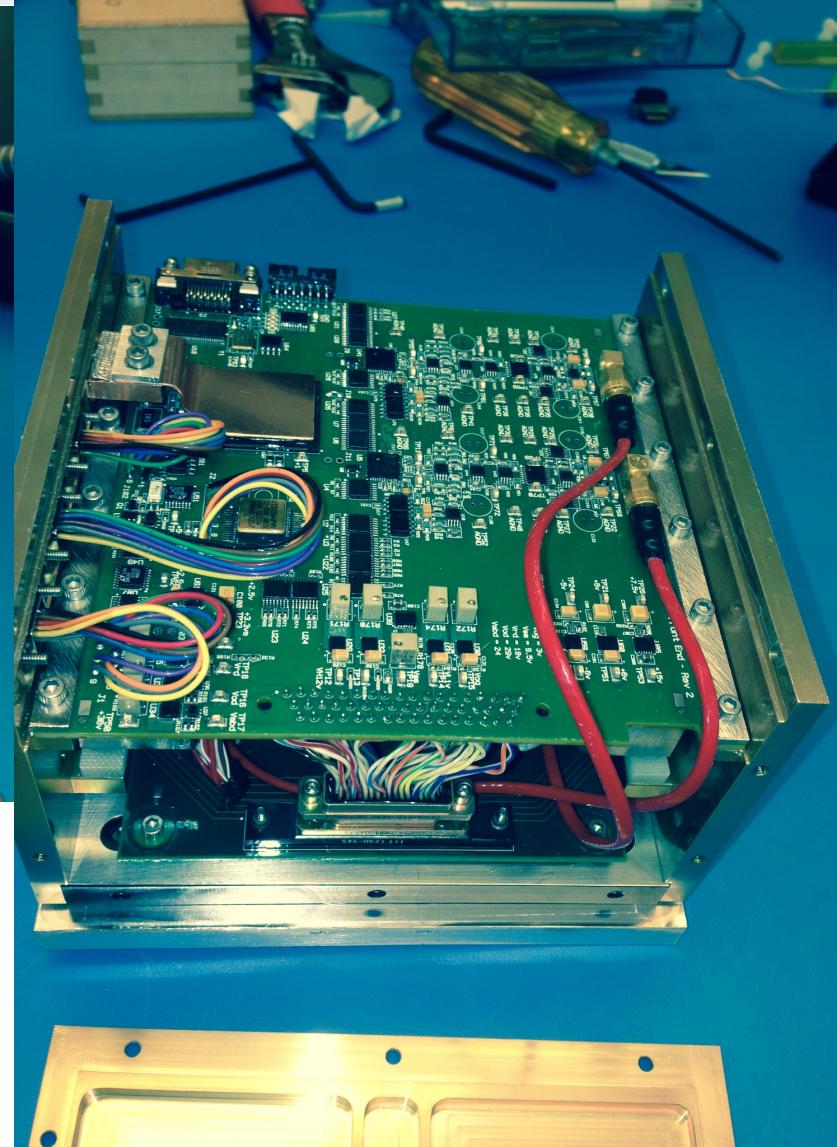
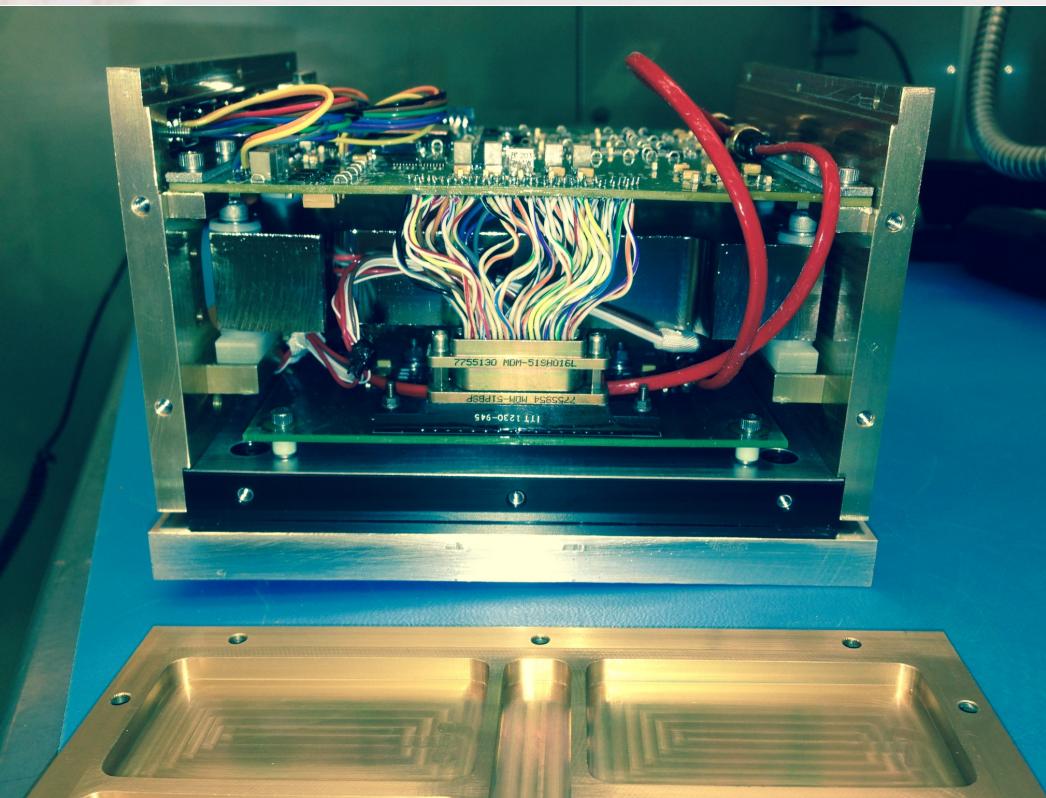


Proposed to fly in Spring 2018.

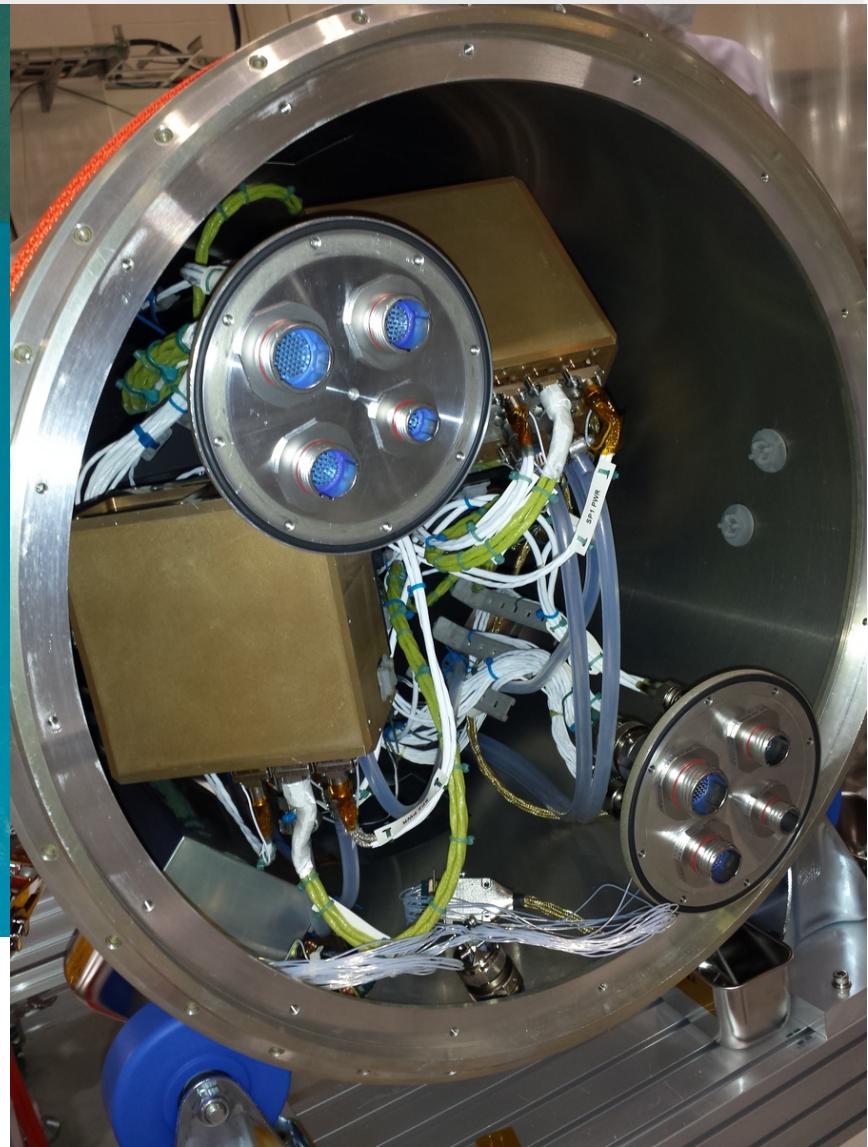
Low Noise Camera Development

- To achieve the 0.03% polarization accuracy required by CLASP, we required detectors with less than 25e- total noise.
- We developed a 512x512 frame transfer camera at MSFC suitable for sub orbital instruments.
- 3 flight cameras were built (2 SP, 1 SJ)
- Each contain a back-thinned e2v CCD57-10 detector, coated with lumogen.
- Noise calculations from flight data demonstrate <6e- noise RMS noise in all cameras.

Low Noise Camera Development



Low Noise Camera Development

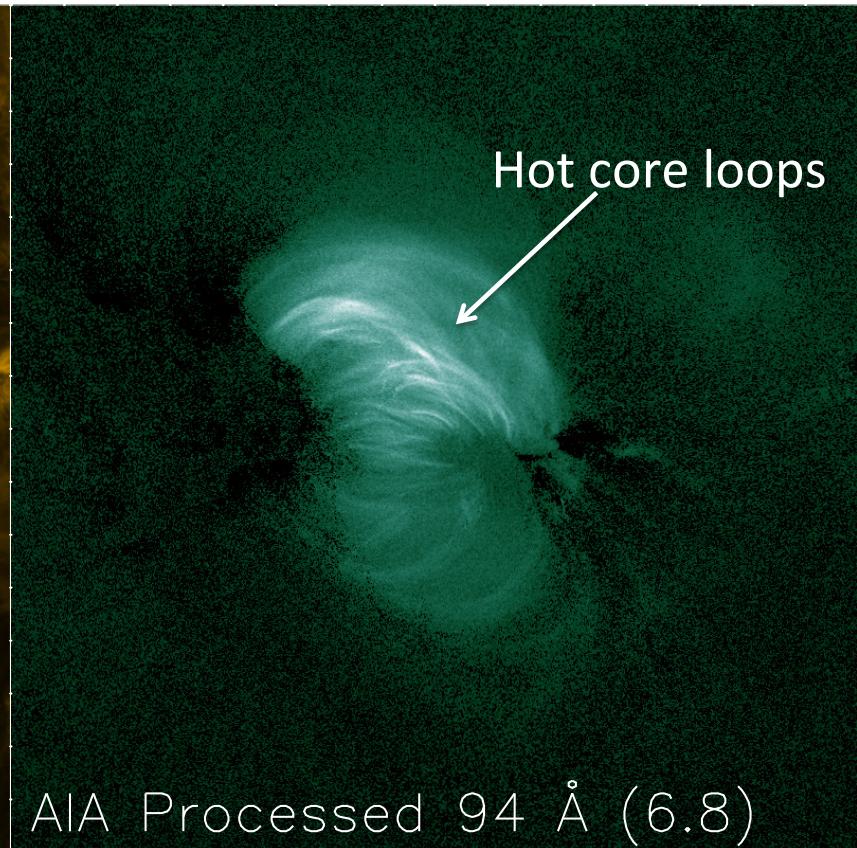
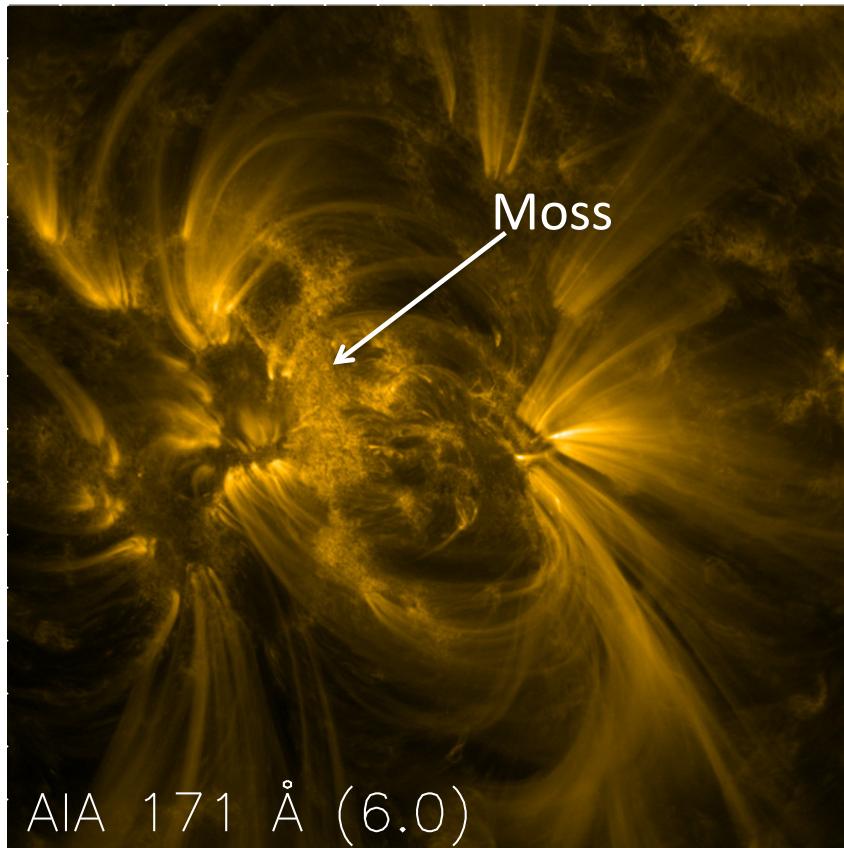


Low Noise Camera Development

- The design is currently being expanded for a 2kx2k CCD.
- Hi-C, MaGIXS, and ESIS (MSU sounding rocket) will make use of the new design.

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

The science goal of MaGIXS is to determine the frequency of heating in active region cores.



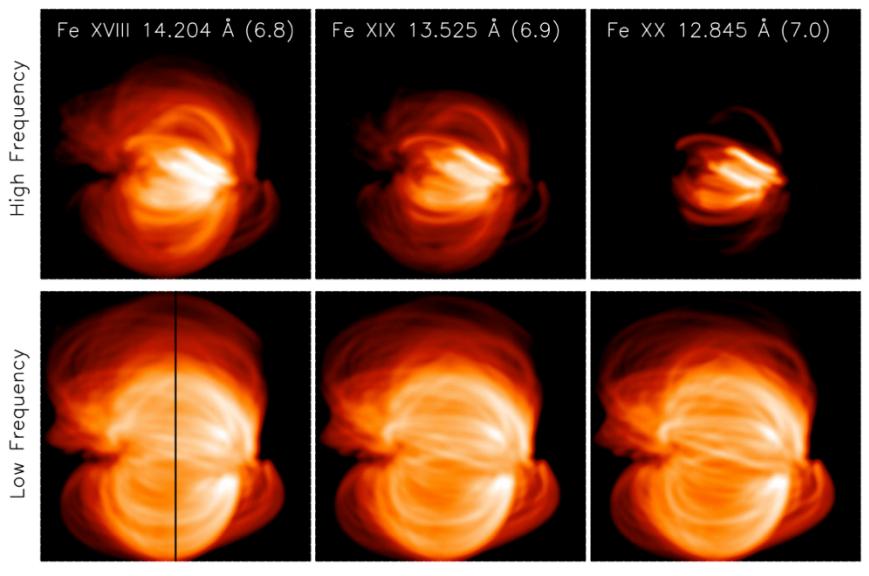
Is heating sporadic (nanoflares) or frequent (waves)?

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

MaGIXS will make four key observations to differentiate between sporadic and frequent heating.

- Relative amount of high temperature plasma
- Elemental abundances
- Temporal variability of high temperature plasma
- Likelihood of non-Maxwellian distributions

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Simulated MaGIXS spectra

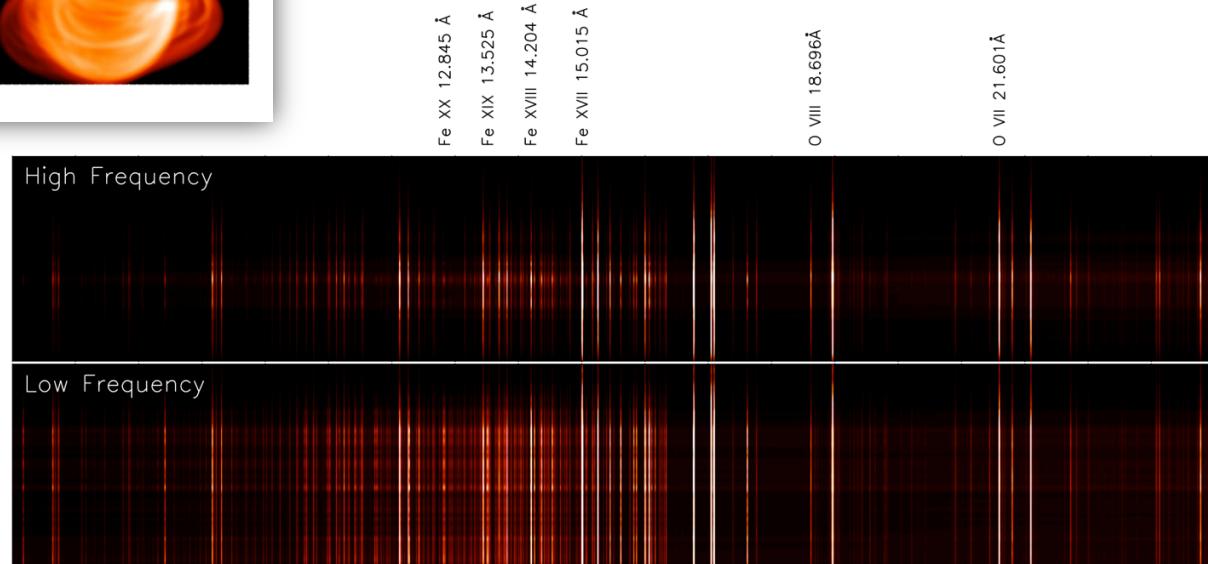
Biggest difference in Fe XX (12.845 Å).

Multiple high temperature spectra lines necessary for interpretation.

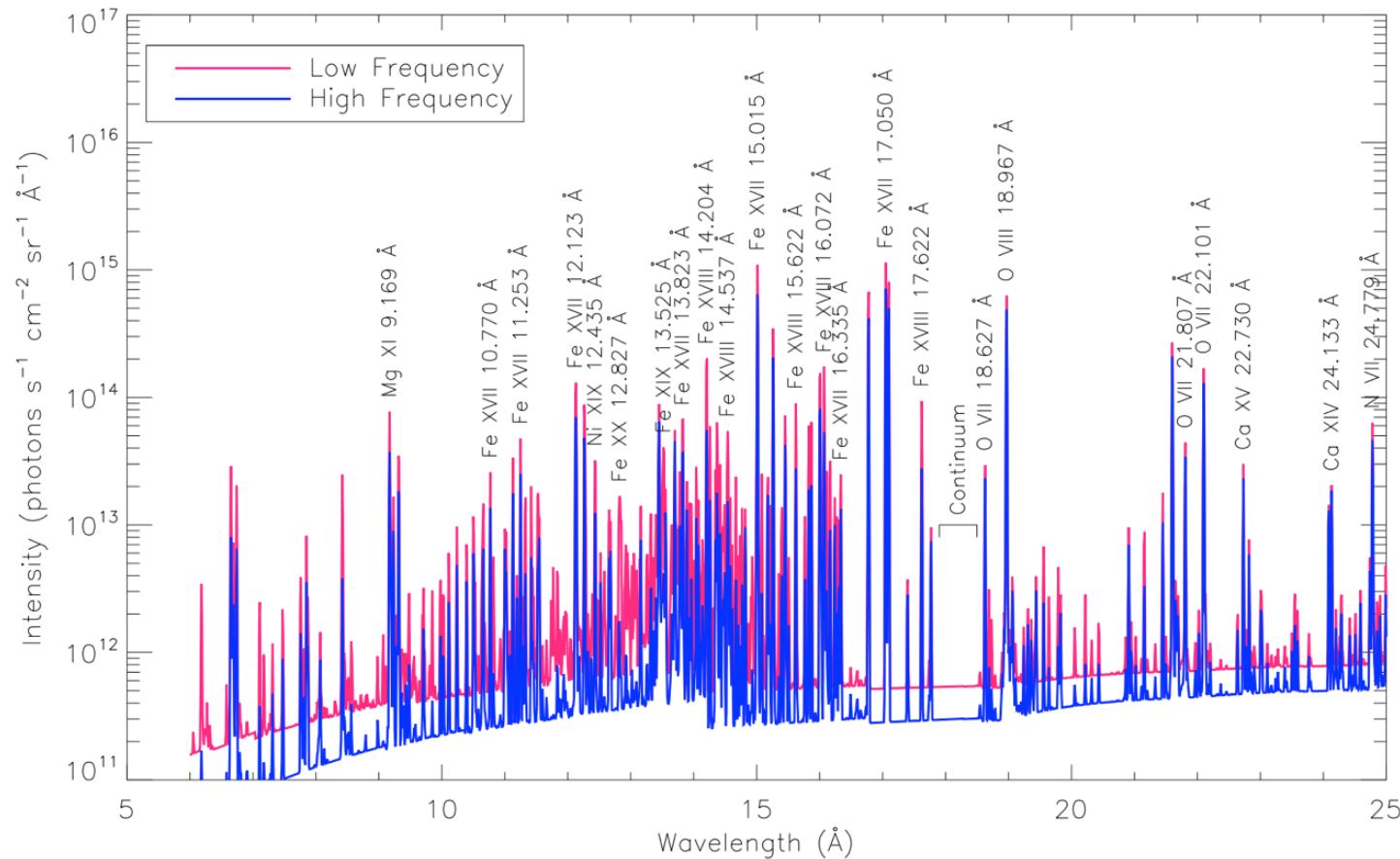
Simulated active region core using 0-D EBTEL:

- Random heating events
- Heating event cadence 1575 s versus 6300 s

Expected emission quite different at higher temperature lines.



Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



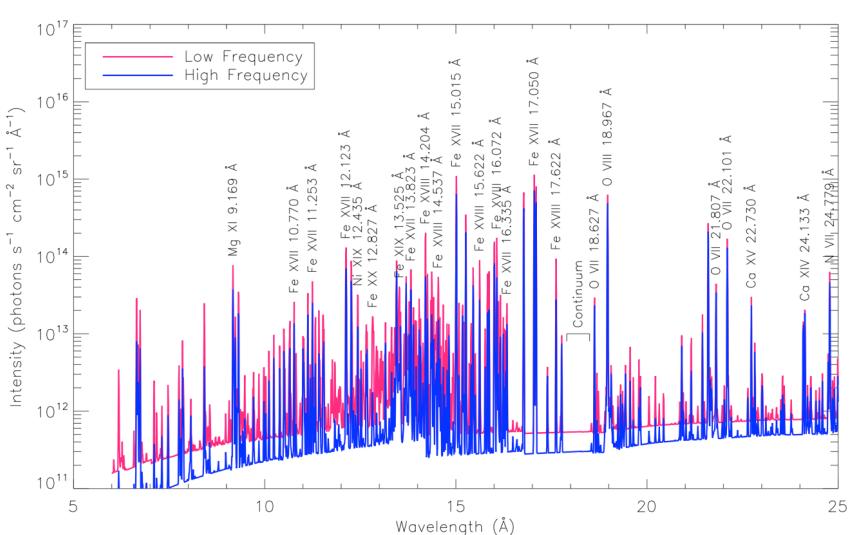
Simulated spectra from a single spatial position along the MaGIXS slit.

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

Trends in variability indicate that the FIP bias is proportional to the plasma's time of confinement.

Abundance measurements may be an indicator of the frequency of heating.

- Photospheric: *sporadic*
- Coronal: *high frequency*

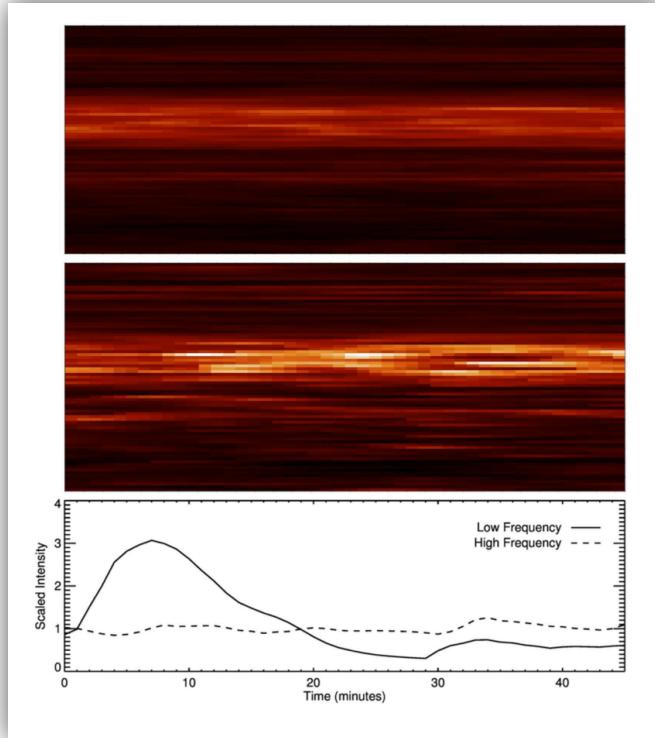


Spectral Line	Log Temperature
Mg XII 8.42 Å	6.9
Mg XI 9.16 Å	6.4
Ne X 12.13 Å	6.6
Ne IX 13.45 Å	6.2
Fe XVIII 14.21 Å	6.8
Fe XVII 15.01 Å	6.6
O VIII 18.97 Å	6.4
O VII 21.60 Å	6.3

Relative abundances largely independent of plasma temperature.

The **spatially and spectrally resolved MaGIXS solar spectrum** will provide relative and absolute abundances for determining the FIP bias in several AR structures.

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



A statistical analysis of AR light curves can also be used to understand heating frequency:

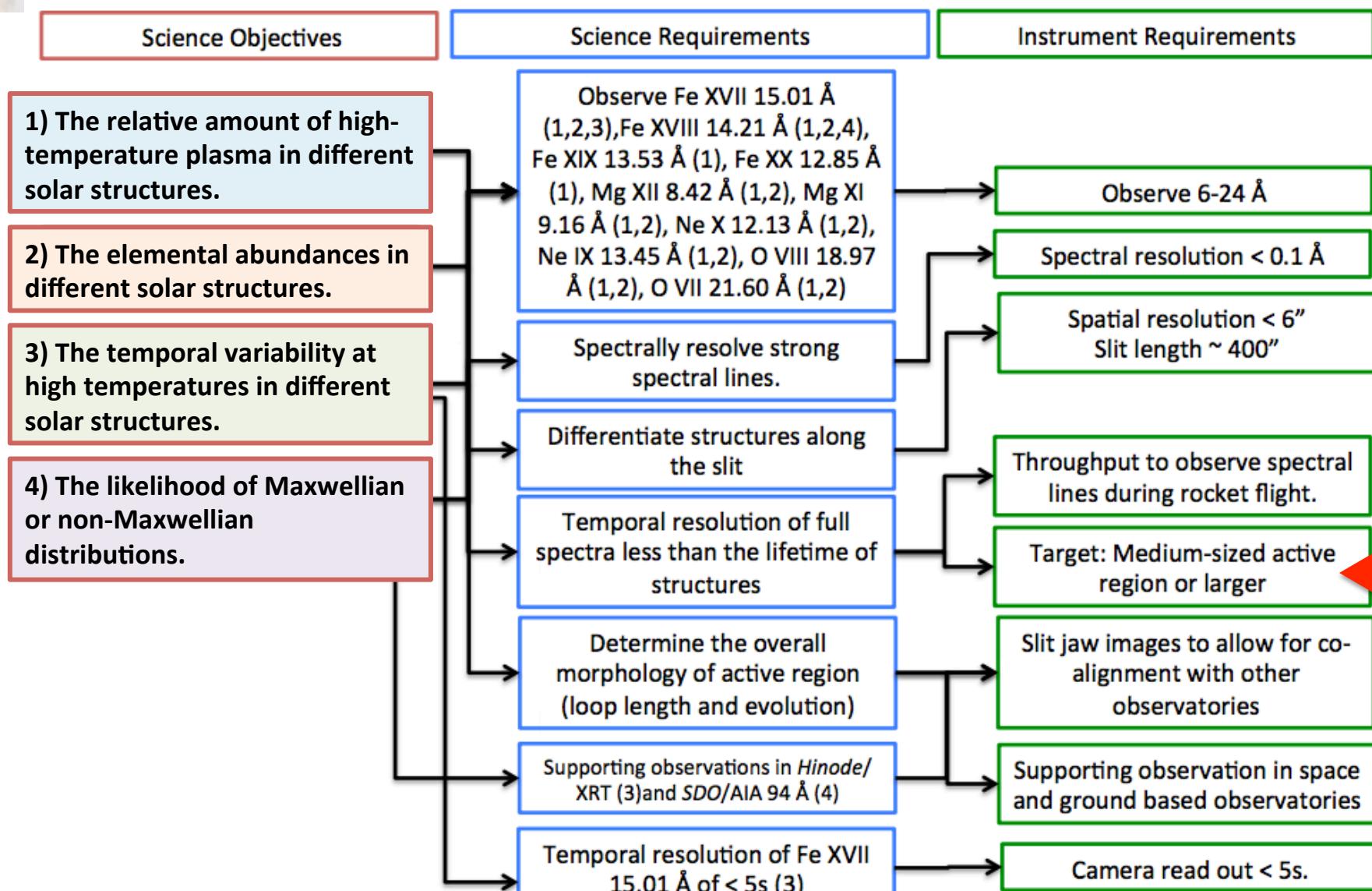
Individual impulsive heating event (low frequency) = steep rise --> slower decay

Impulsive heating results in a skewed distribution, definitely measurable by MaGIXS. Use Fe XVII lightcurves to determine if *Hinode*/XRT skewness due to high temperature fluctuations versus cool contributions or noise.

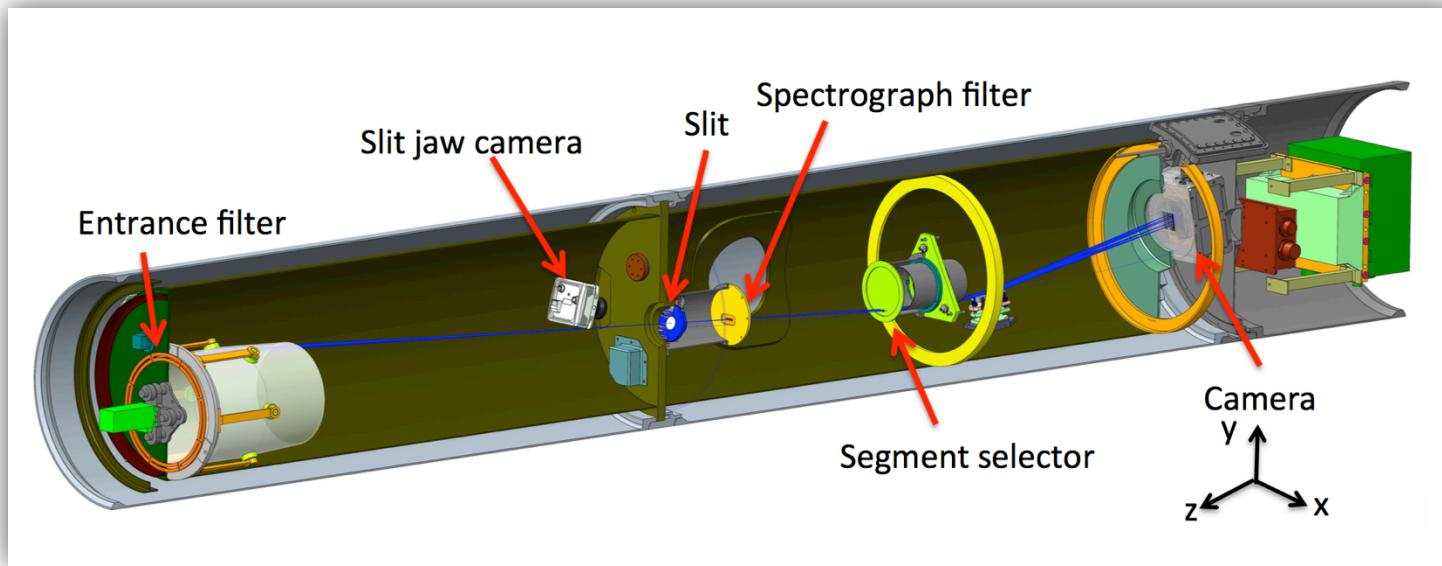
If high-T variability confirmed, **timescales can be used to determine the heating frequency.**

Non-Maxwellian distributions would strongly indicate impulsive, infrequent coronal heating from magnetic reconnection or wave-particle interactions. MaGIXS spectral range optimal for this search due to high-energy excitation thresholds (e.g., ratio between Fe XVIII lines and *SDO/AIA* 94 Å bandpass).

Marshall Grazing Incident X-ray Spectrometer (MaGIKS)



Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



Telescope: Wolter Type-I
Effective Focal Length ~ 1 m

Slit jaw imaging system for pointing and co-alignment

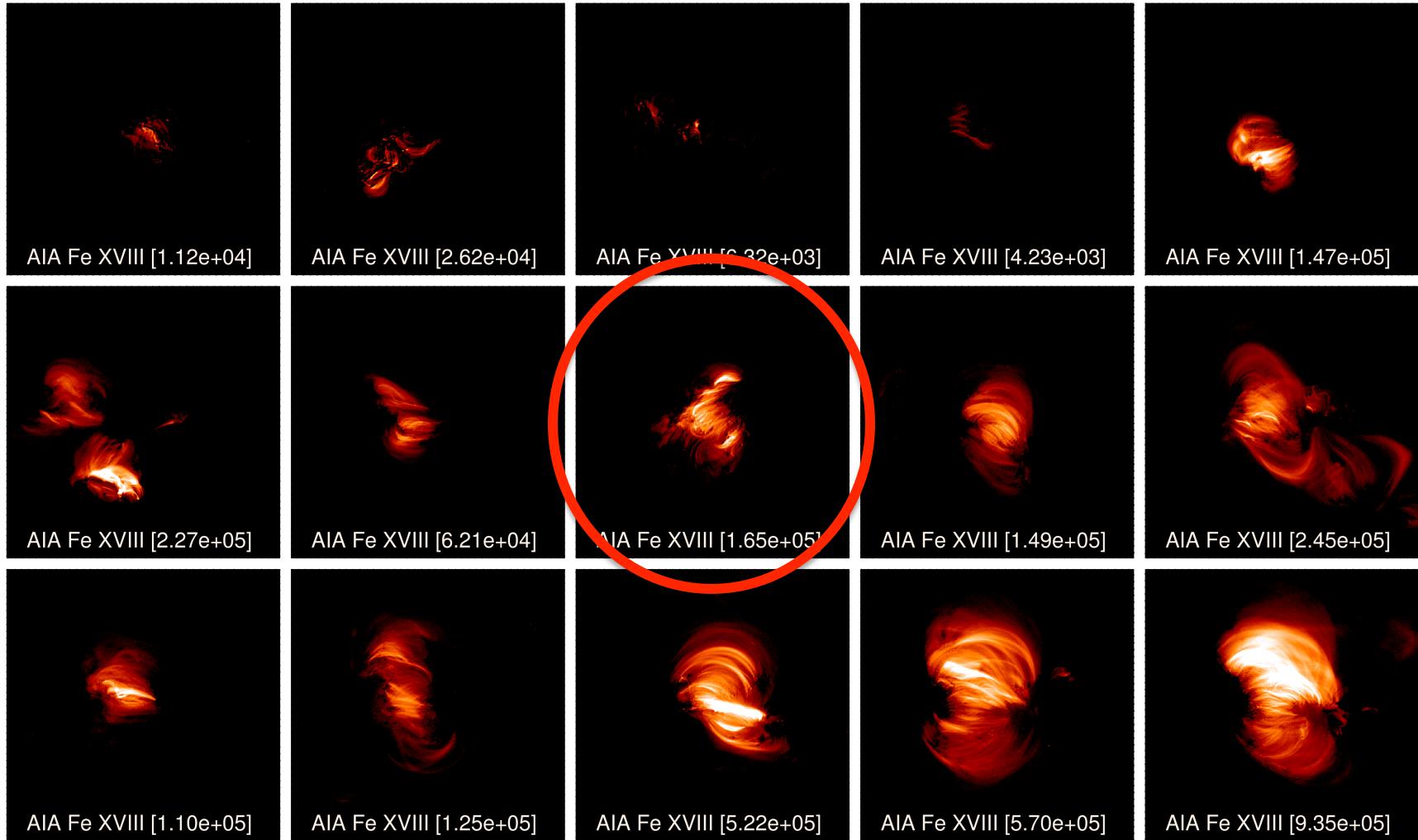
Detector : Low noise, 2kx1k frame transfer

Spectrograph: Two matched parabolic mirrors + Grating
6.0 - 24.0 Å (0.5 - 2.0 keV)
11 mÅ / pixel
2.8 arcsec / pixel

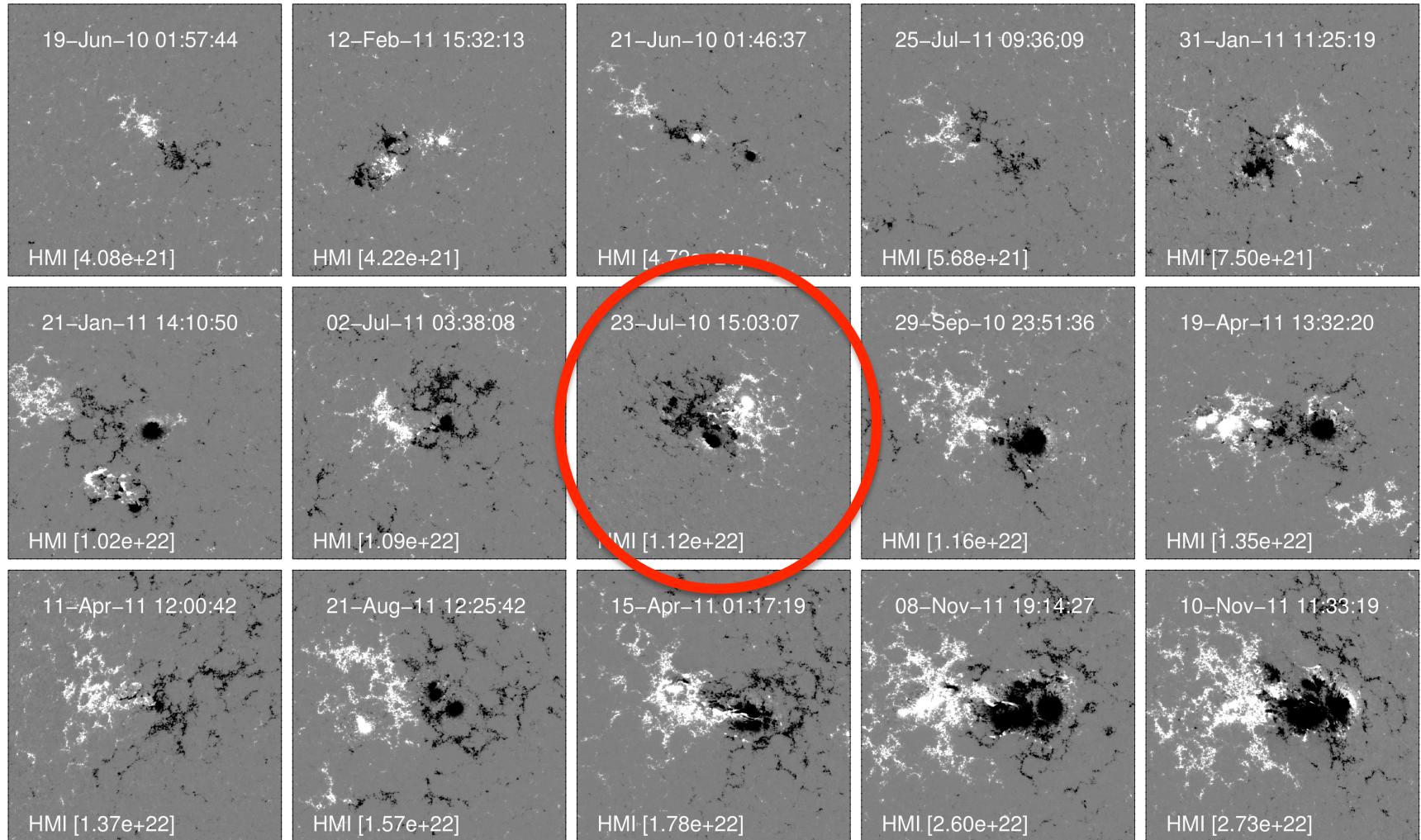
Grating: Blazed Planar Varied Line Space

MaGIXS will be launched in summer 2018 or 2019.

Marshall Grazing Incident X-ray Spectrometer (MaGIXS)

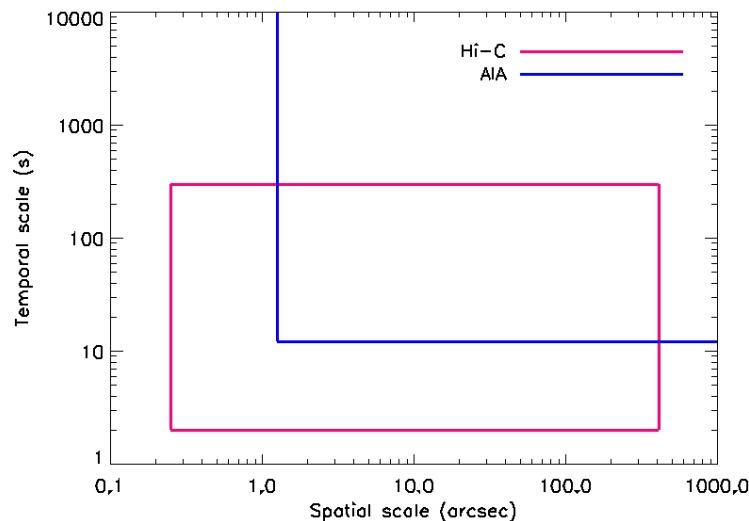
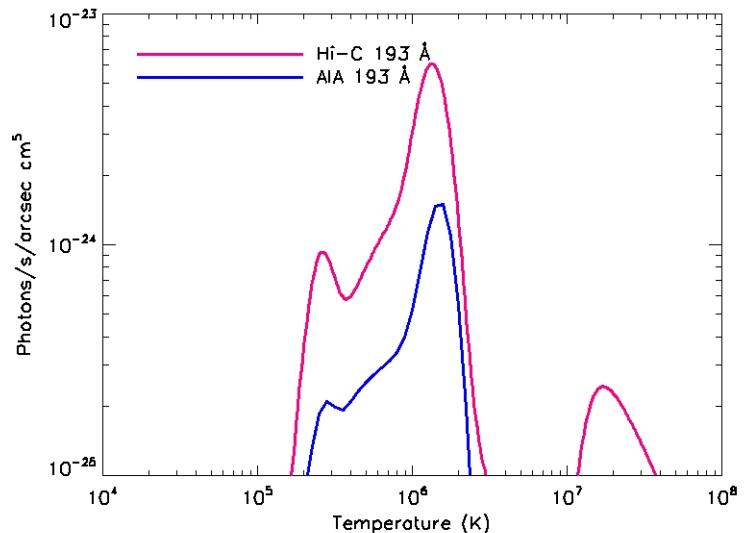


Marshall Grazing Incident X-ray Spectrometer (MaGIXS)



High-resolution Coronal Imager (Hi-C)

- The Hi-C 193 Å passband is similar to the 193 Å passband on the Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA).
- Hi-C has roughly 5 times the effective area of AIA.
- The cadence of Hi-C is 2.5 – 6 times better than AIA.
- Hi-C collected data for 345 s.
- Small shift in pointing during flight
- Full frame (4kx4k) data
 - 30 full resolution images
 - 2 s exposures / 5 s cadence
- Partial frame (1kx1k) data
 - 86 full resolution image
 - 0.5 s exposures / 1.4 s cadence

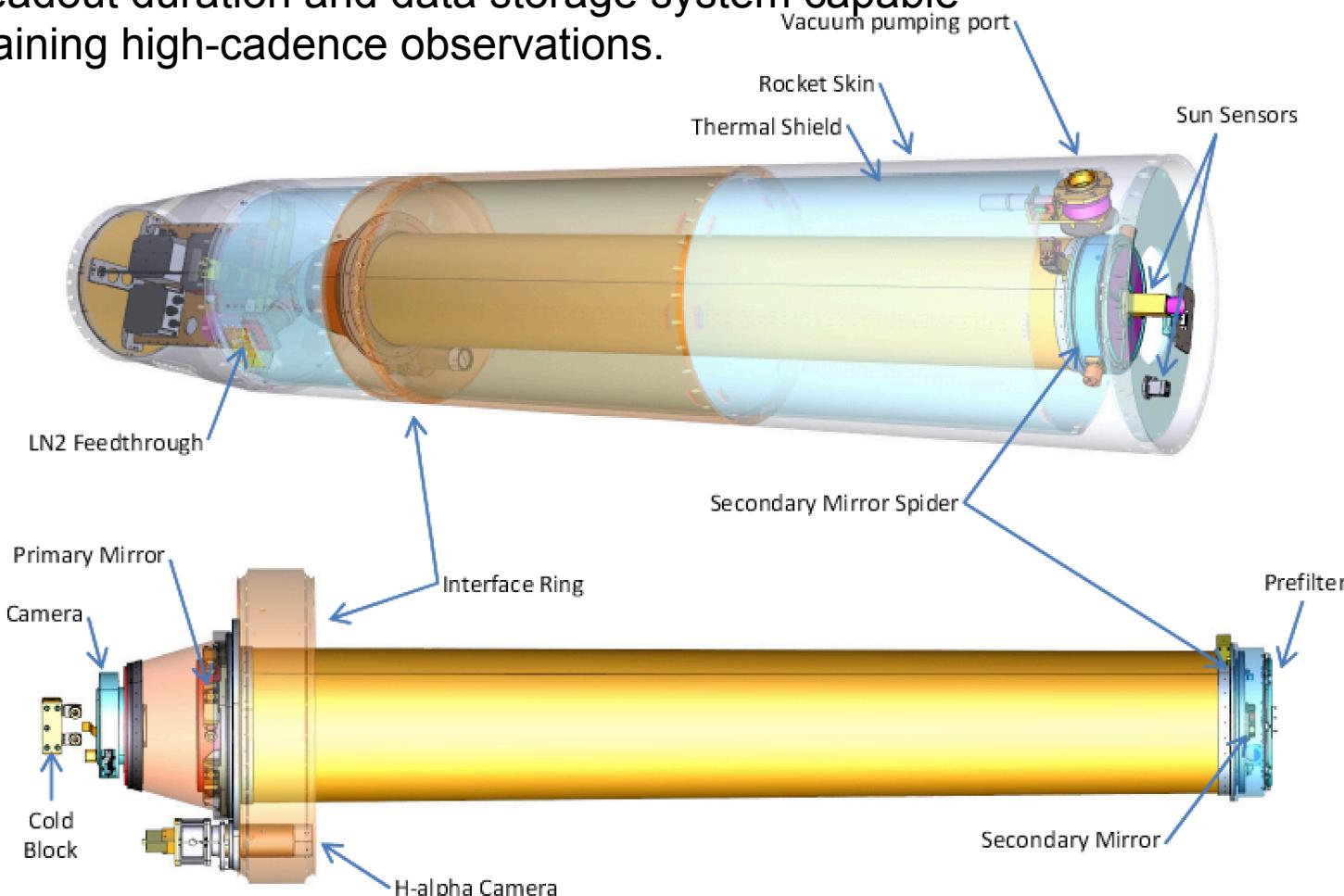


High-resolution Coronal Imager (Hi-C)

Telescope design capable of ~150km spatial resolution

Pointing stability necessary to achieve resolution goal

Image readout duration and data storage system capable of maintaining high-cadence observations.



High-resolution Coronal Imager (Hi-C)

*Hi-C Launch
July 11, 2012*



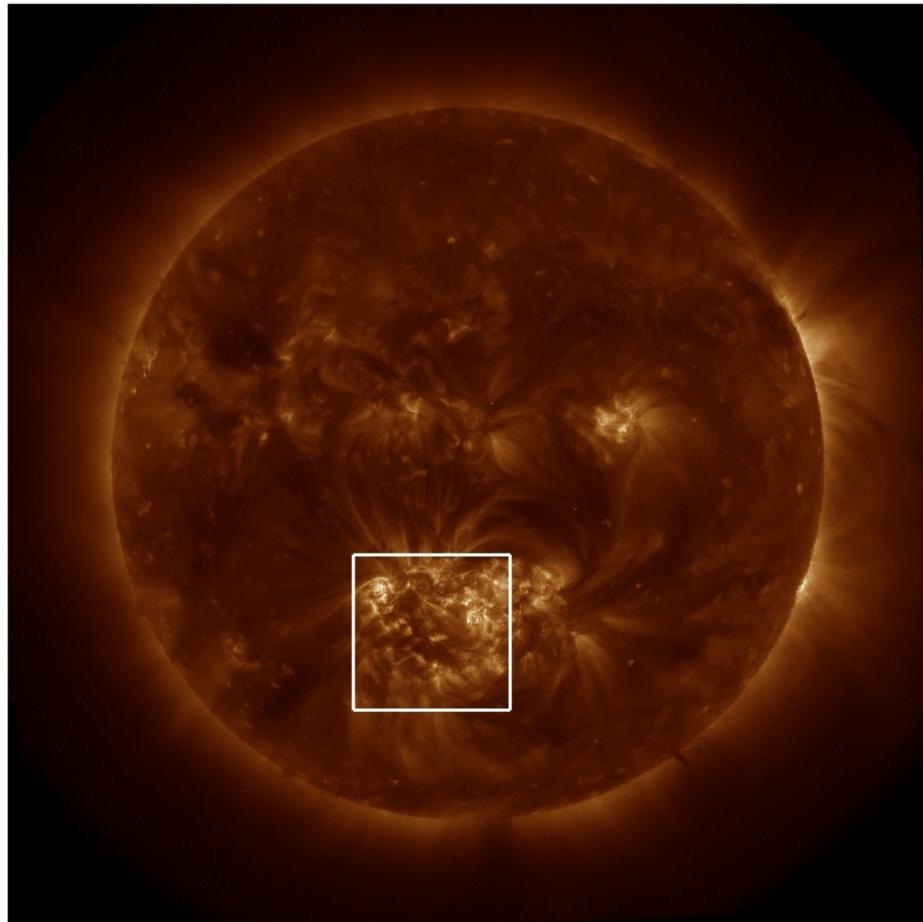
Hi-C recovery team

Hi-C rocket with parachute

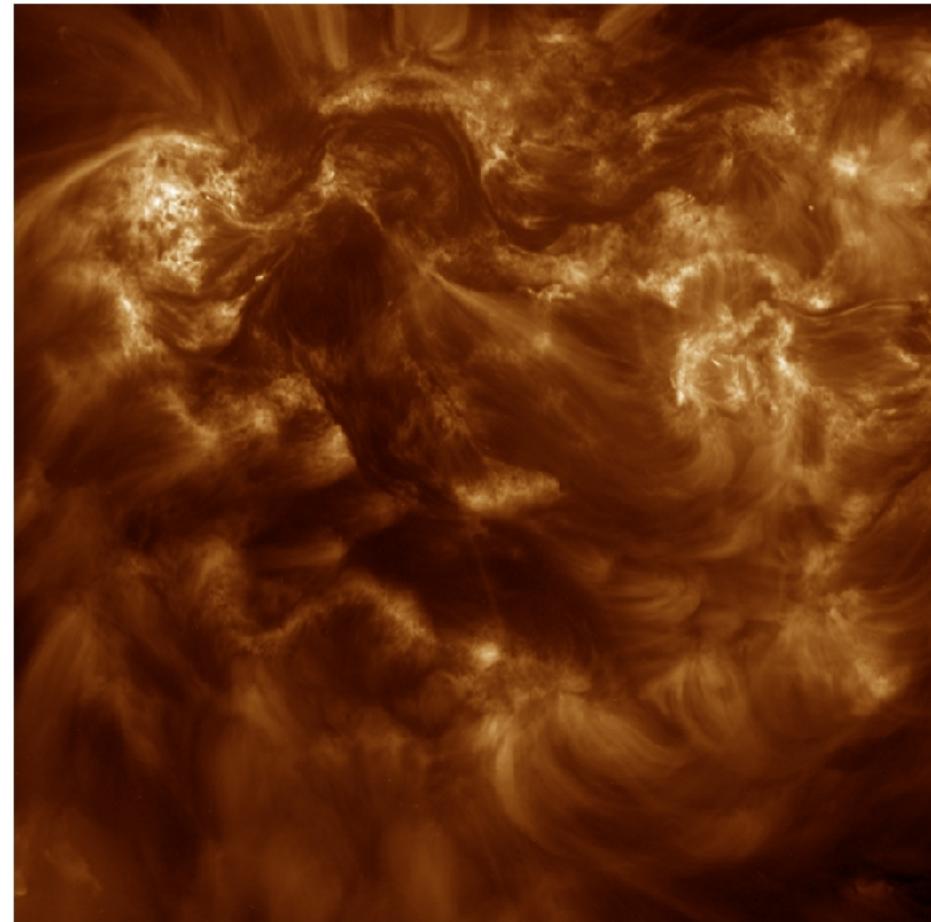


High-resolution Coronal Imager (Hi-C)

AIA 193-Å 11-Jul-2012 18:55:07



Hi-C Field of View

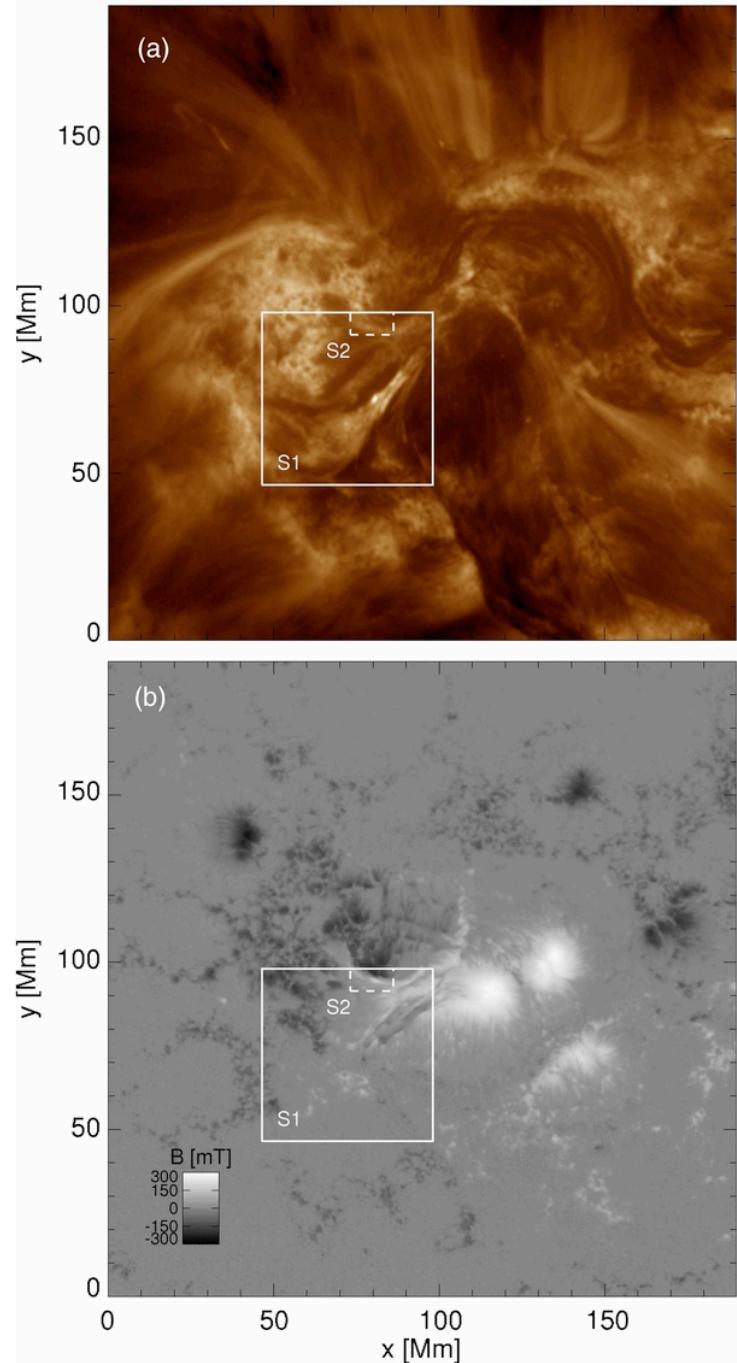
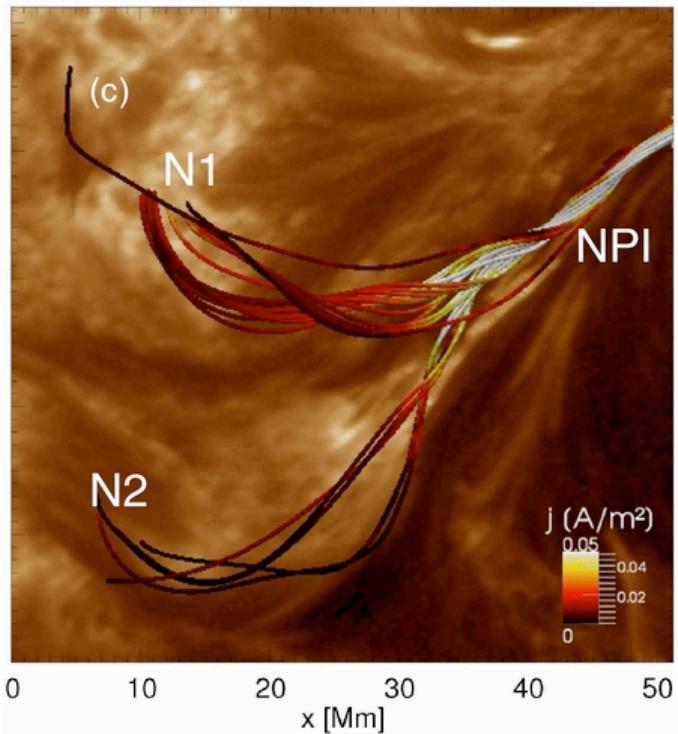


The Hi-C target was Active Region 11520
July 11, 2012

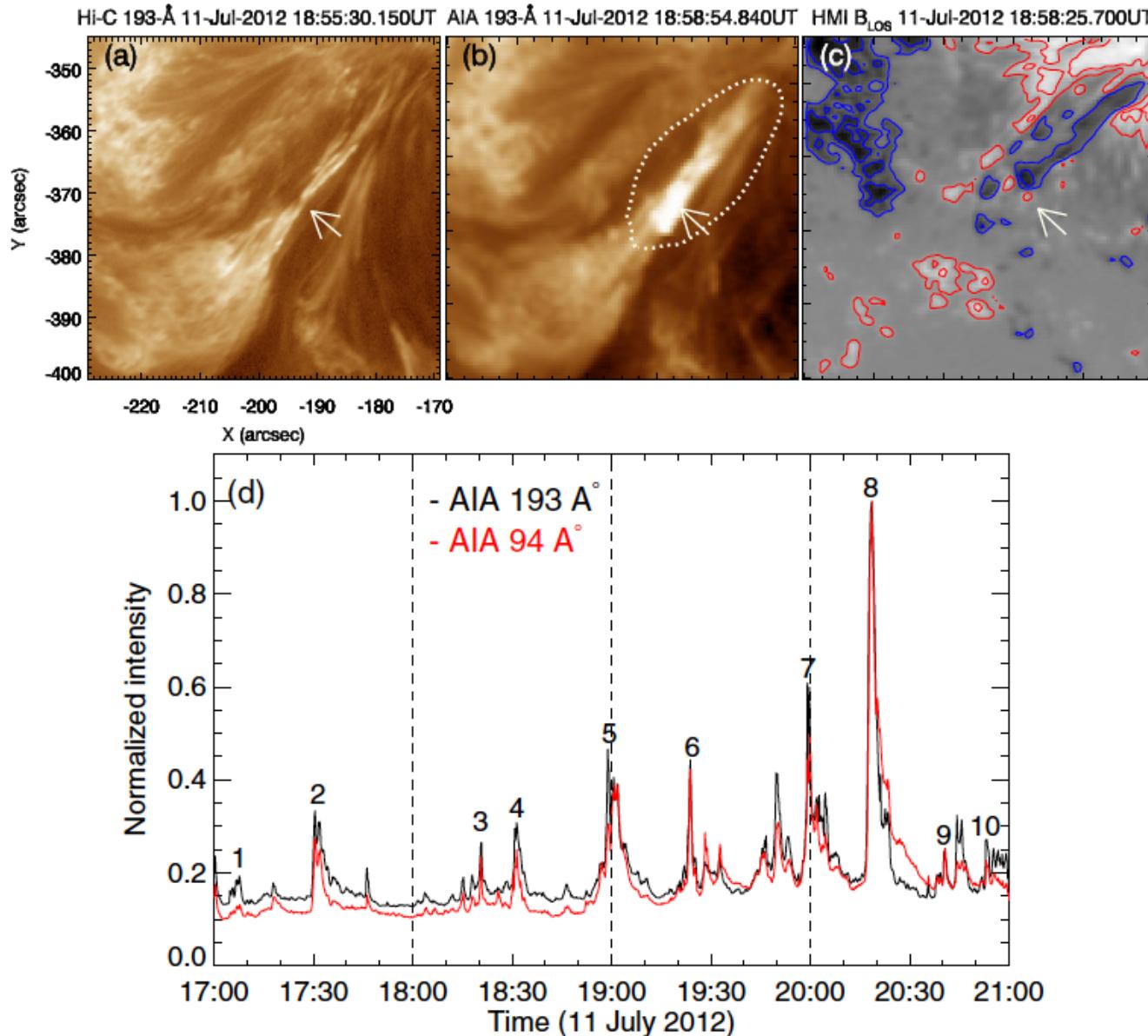
Modeling the braided field

NLFFF extrapolation confirms the braided structure, and free magnetic energy estimates in the given volume

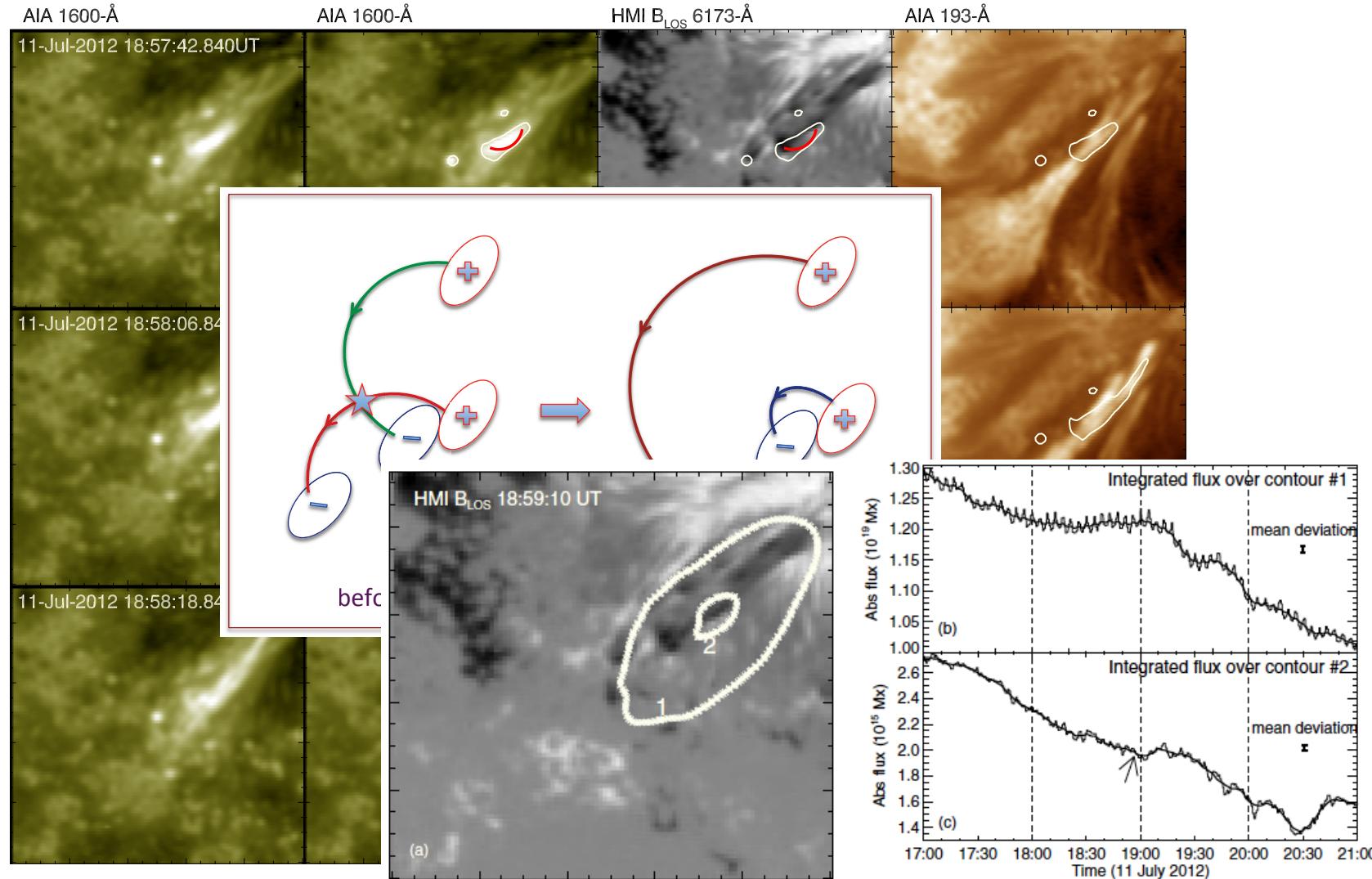
Thalmann, Tiwari & Wiegmann, 2014, ApJ



External triggering of subflares...

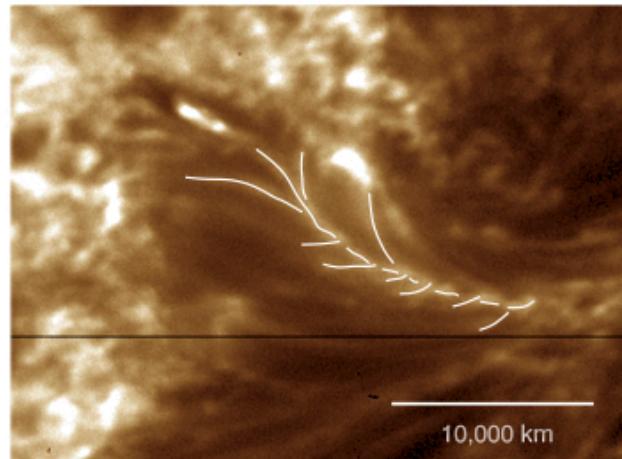


External triggering of subflares...

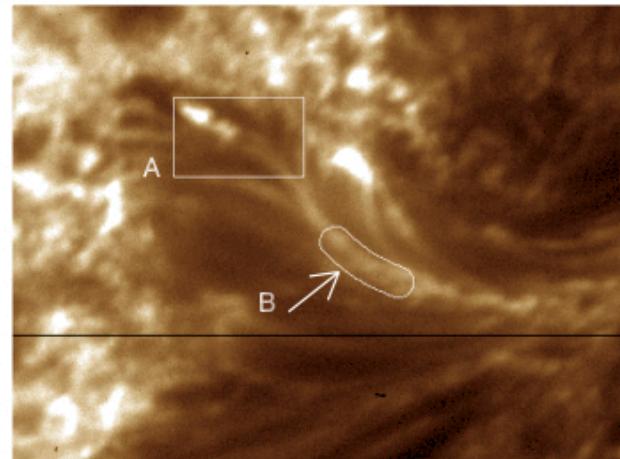


High-resolution Coronal Imager (Hi-C)

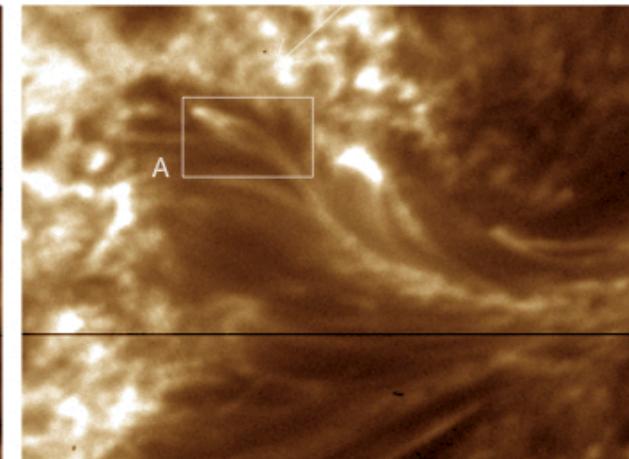
a Hi-C 193-Å: 18:53:28



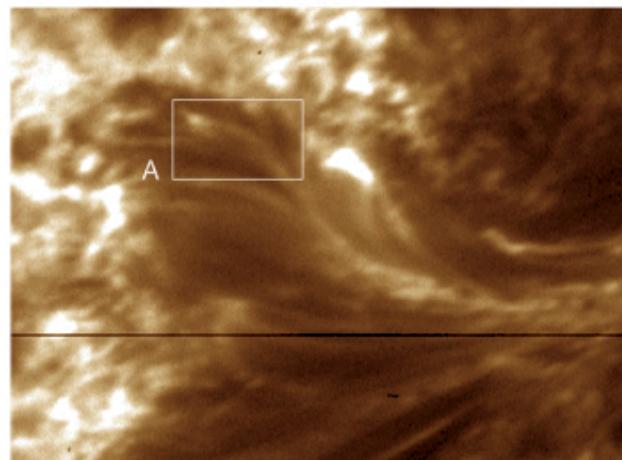
b Hi-C 193-Å: 18:53:45



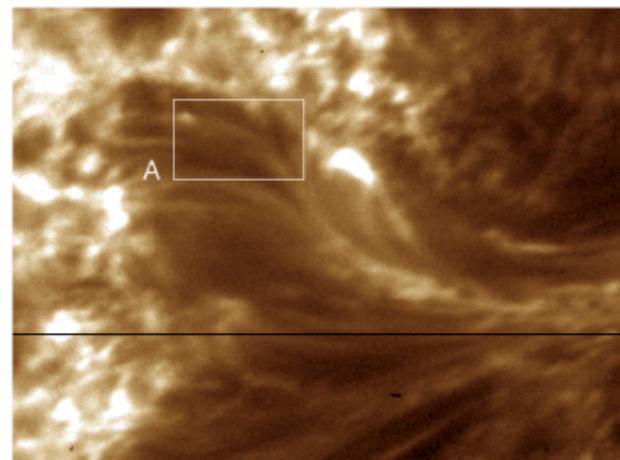
c Hi-C 193-Å: 18:54:13



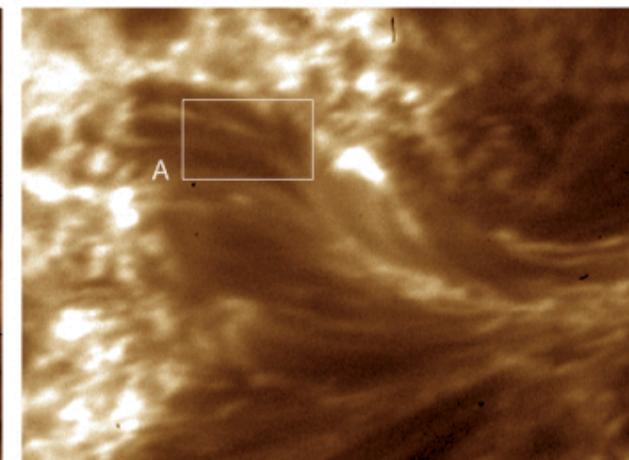
d Hi-C 193-Å: 18:54:41



e Hi-C 193-Å: 18:55:08



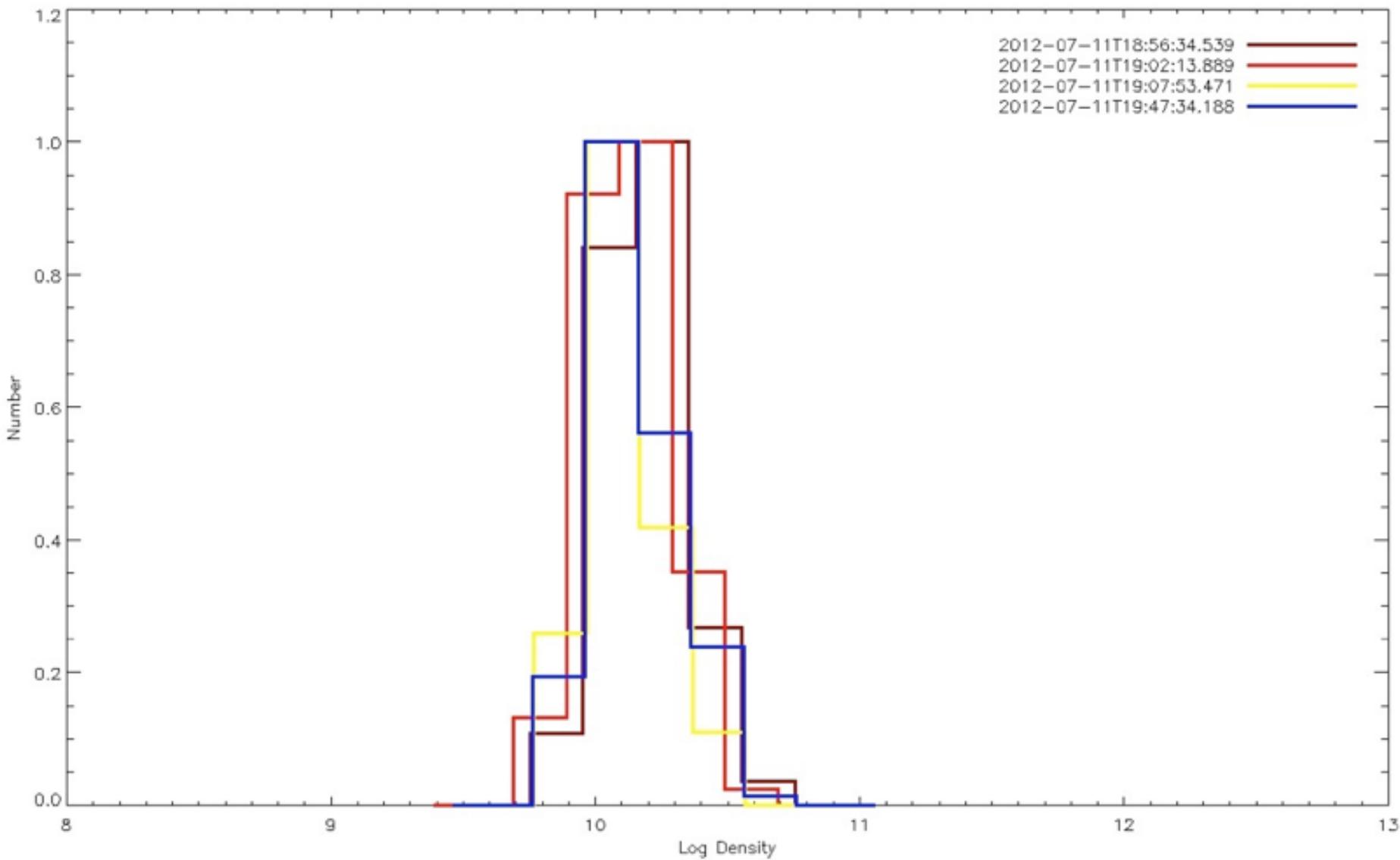
f Hi-C 193-Å: 18:55:36



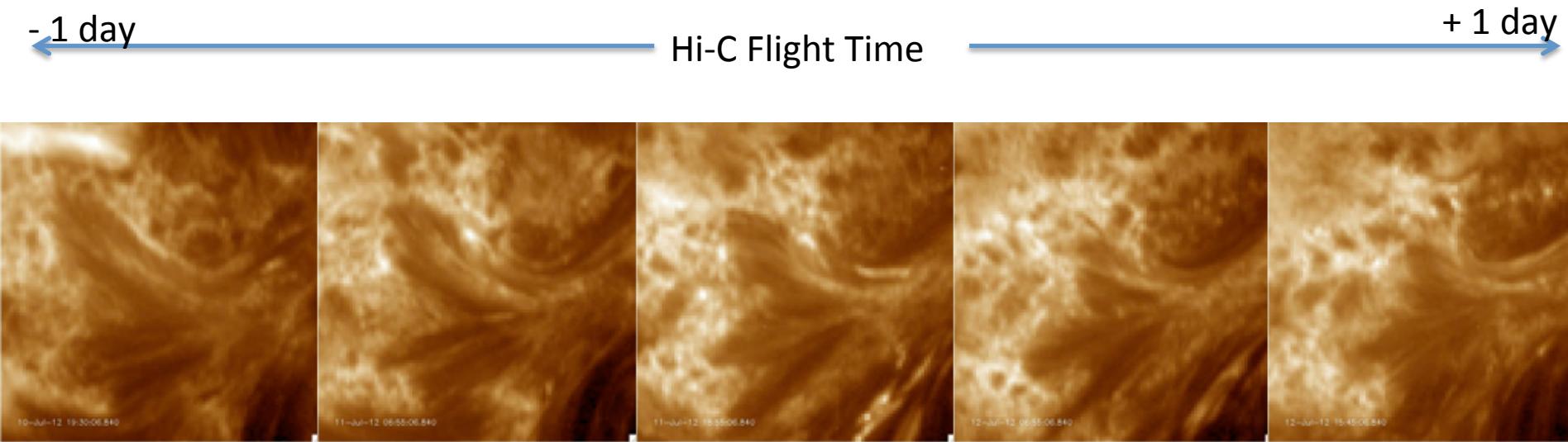
Multiple strands join into this structure. It appears to unwind during Hi-C observations.

Cirtain et al, 2013, Nature

High-resolution Coronal Imager (Hi-C)



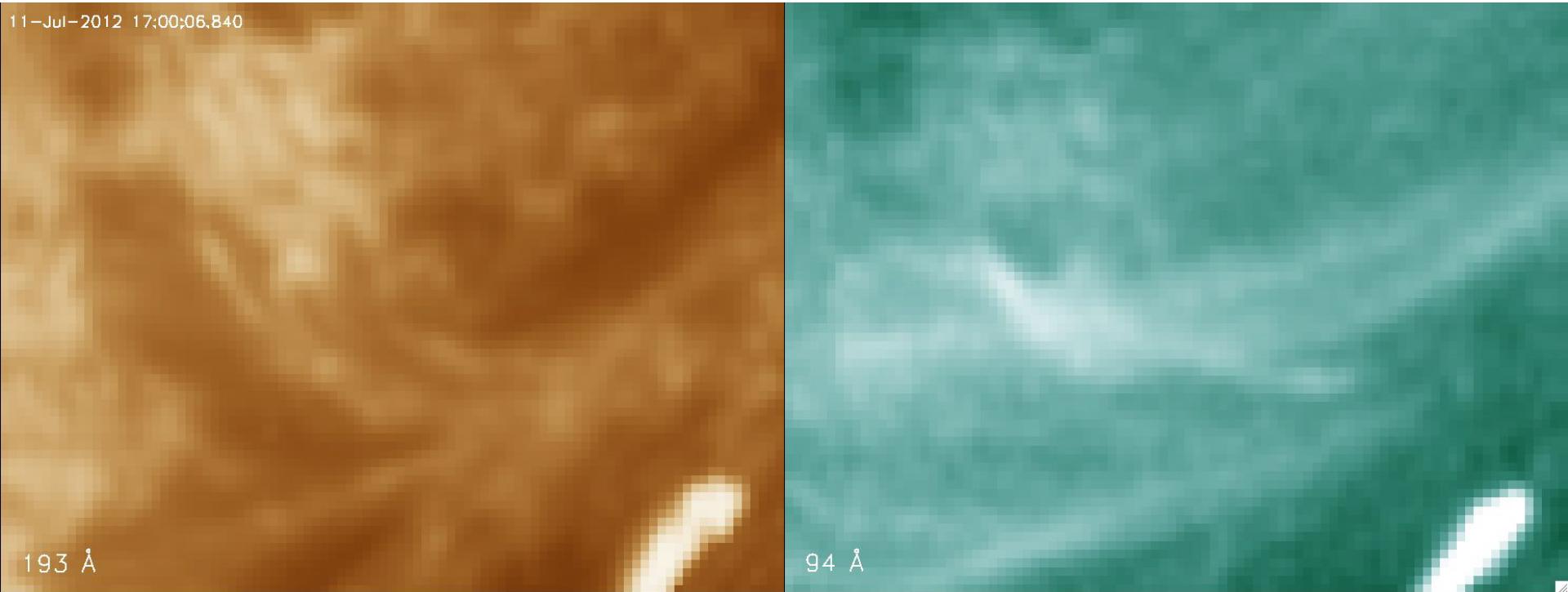
High-resolution Coronal Imager (Hi-C)



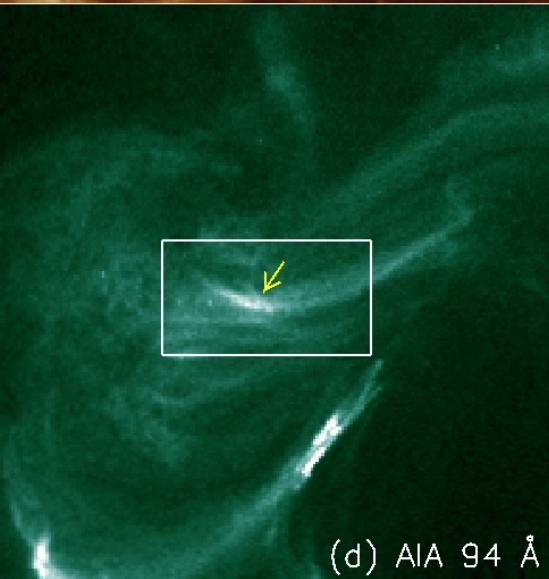
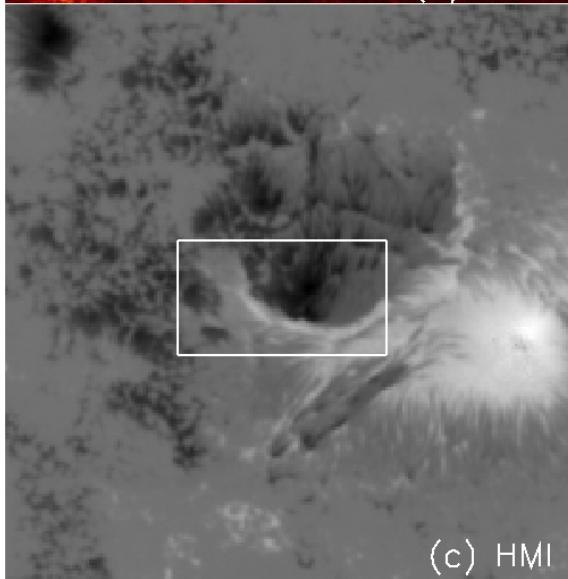
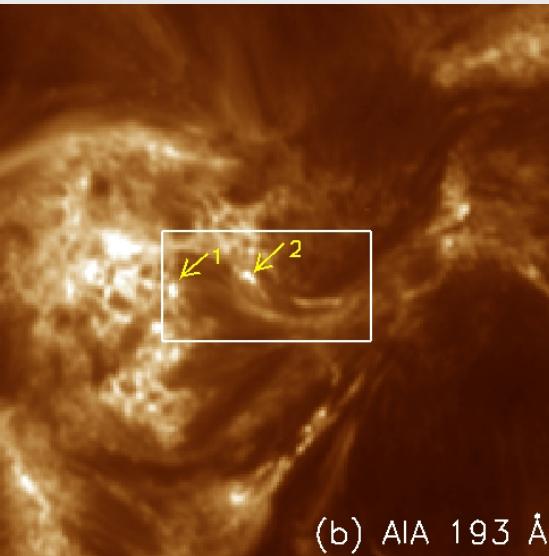
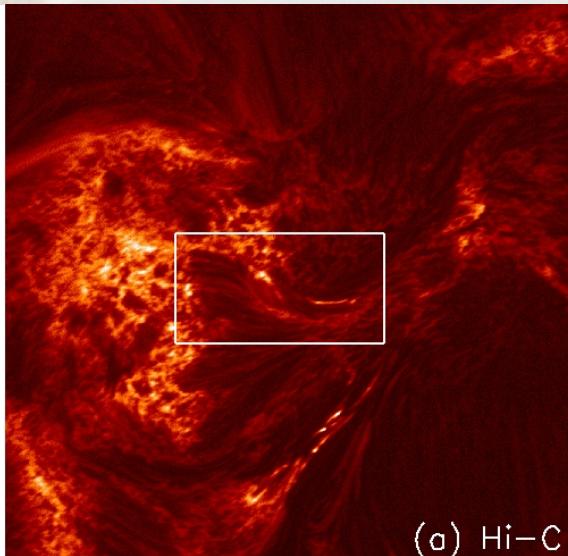
This is a long lived structure and is evident +- 24 hours from the Hi-C flight.

High-resolution Coronal Imager (Hi-C)

11-Jul-2012 17:00:06.840



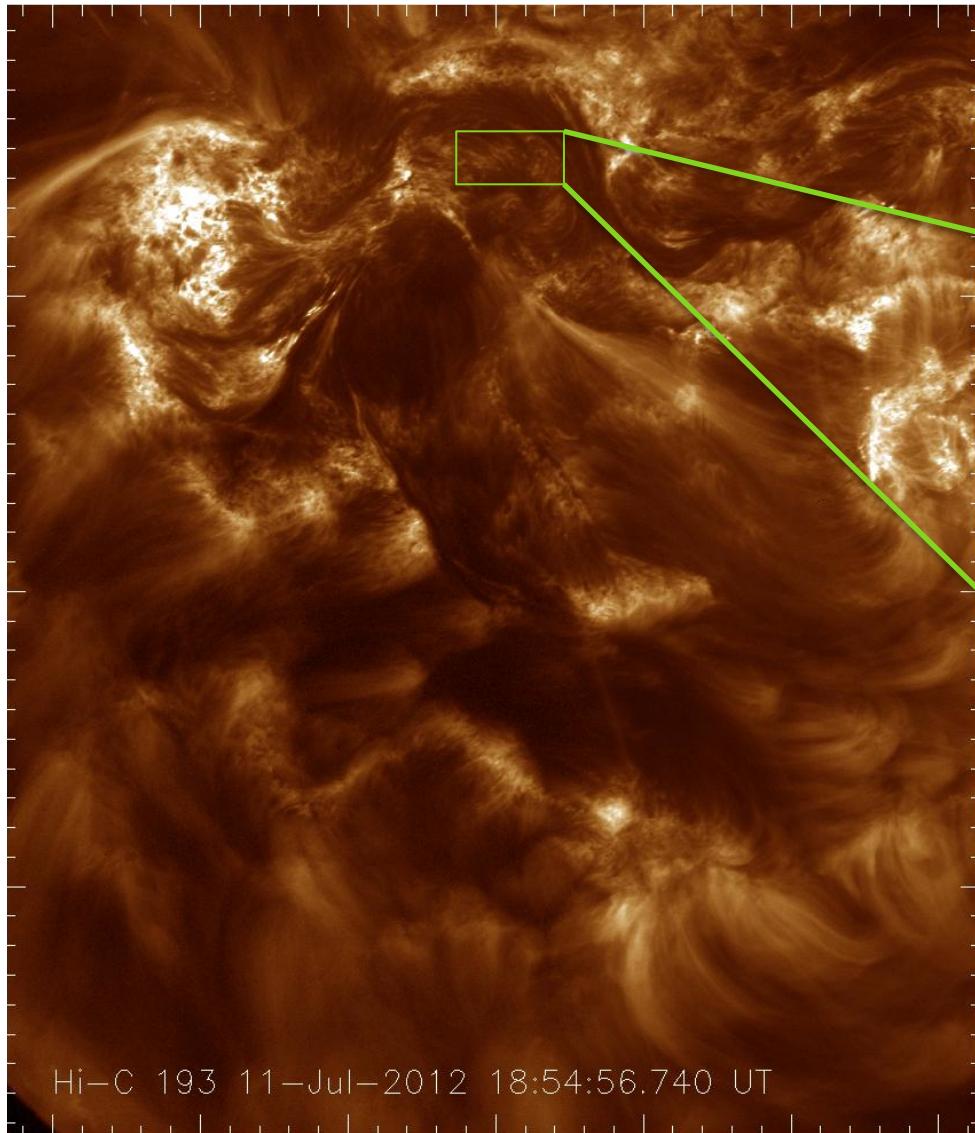
High-resolution Coronal Imager (Hi-C)



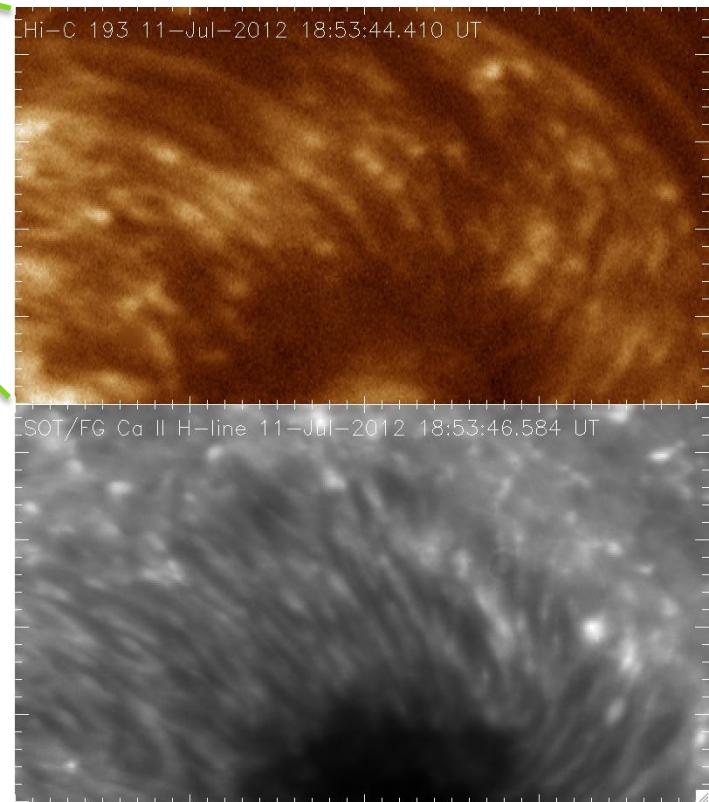
Brightenings in/near braided structure are associated with high temperature evolving loops.

Bright penumbral dots and penumbral microjets

Hi-C 193 Å



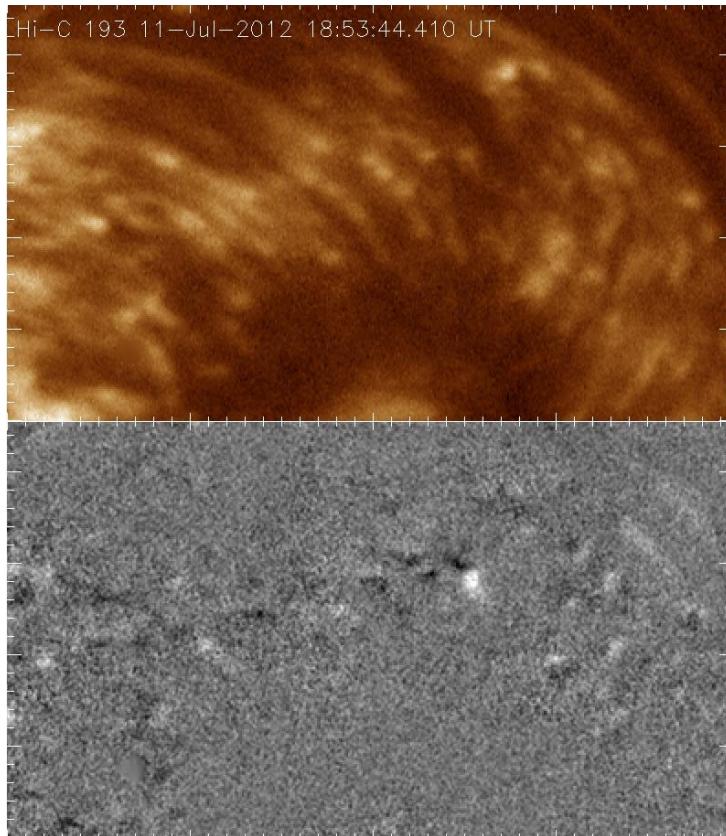
Penumbra; 18:53:44-18:55:30UT



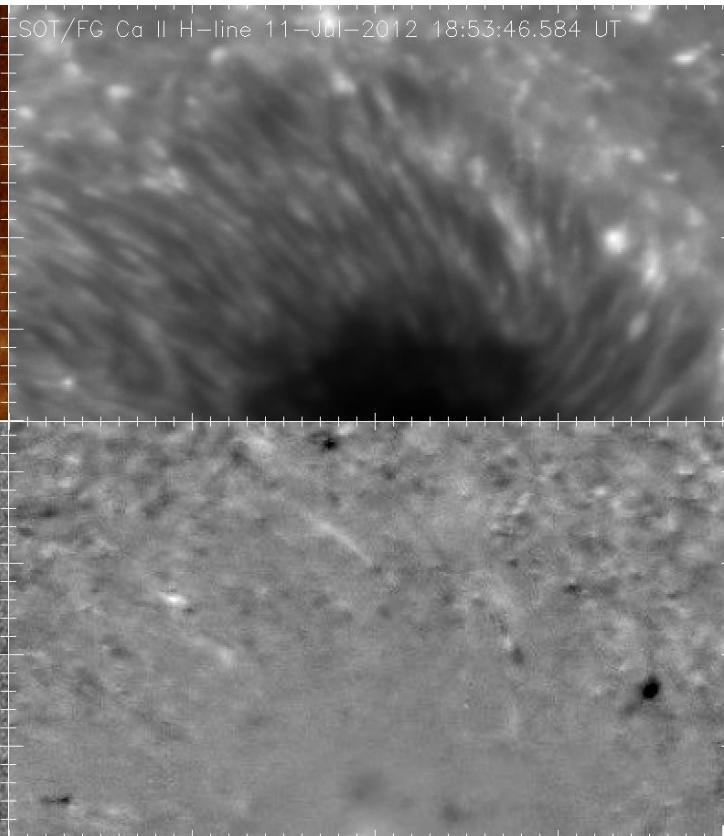
Hinode/SOT/FG Ca II H-line

Bright penumbral dots and penumbral microjets

Hi-C 193 Å

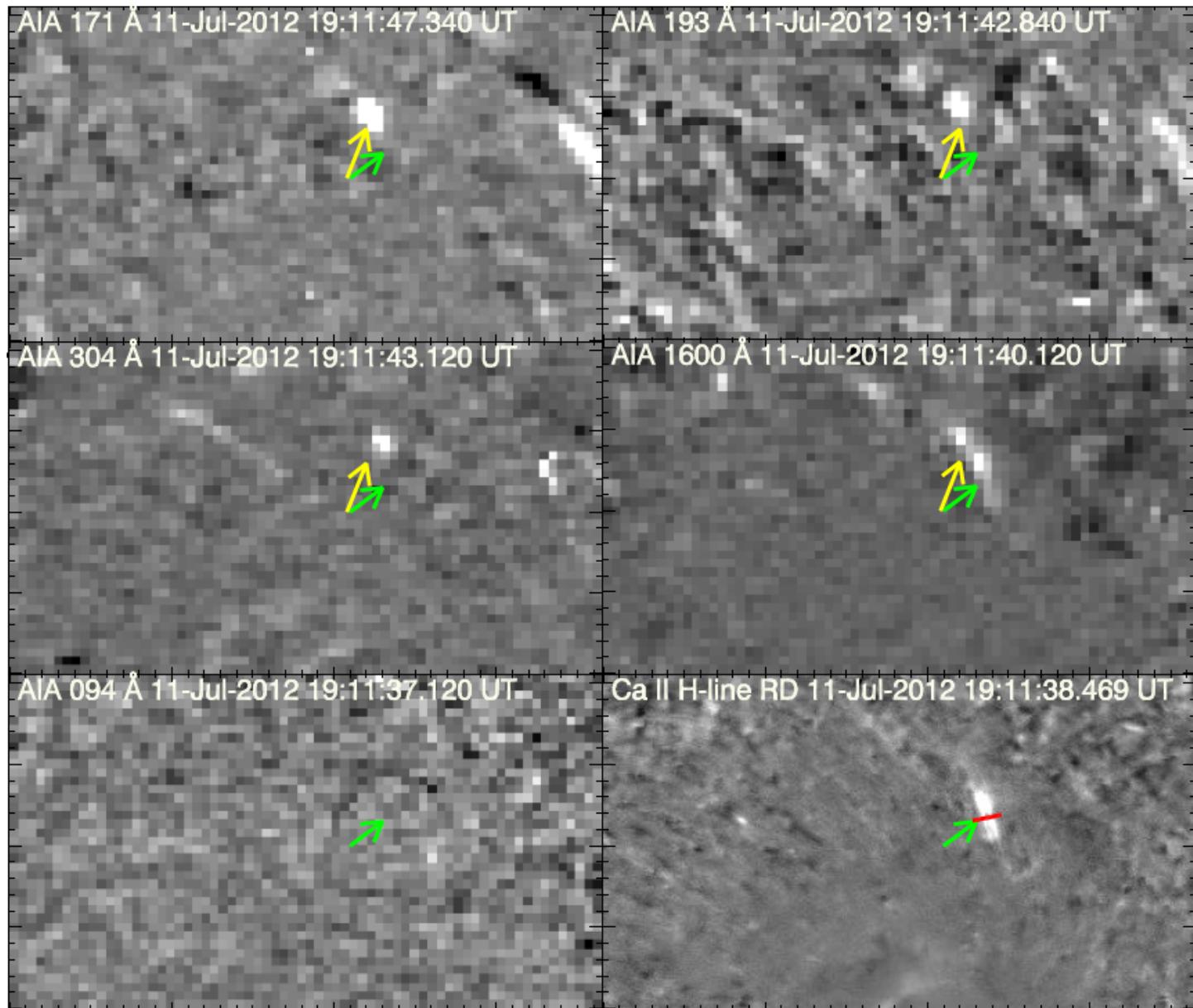


SOT/FG Ca II H-line

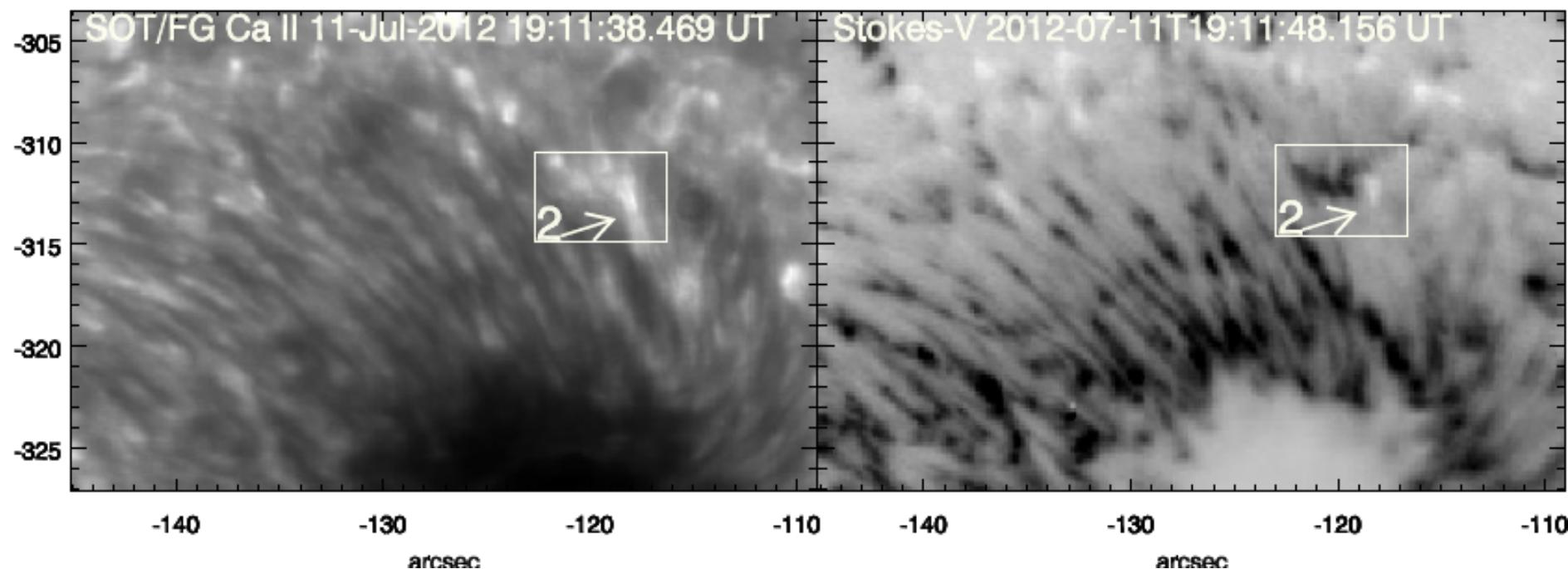


Lower frames are running differences

Larger PJs: Coronal signatures



Mixed polarity at the feet of larger PJs:



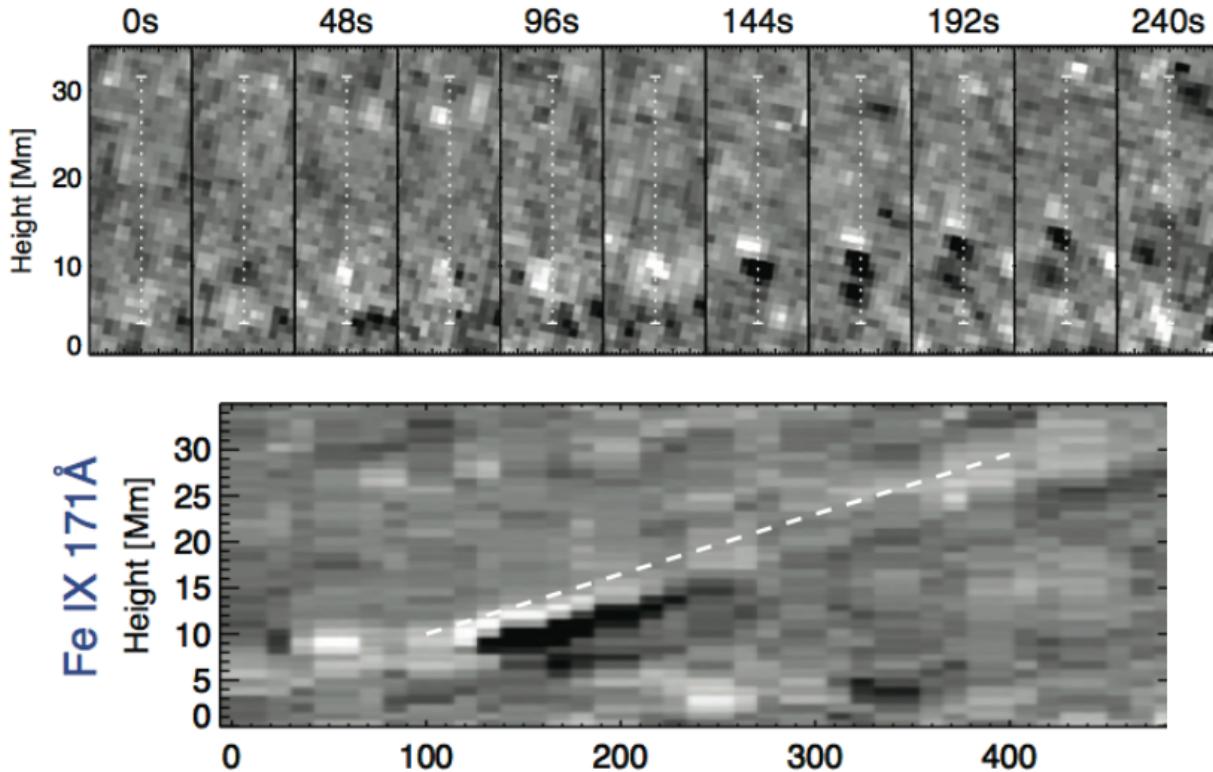
Hi-C II – Exploring the Chromospheric-Coronal Connection

IRIS has shown many chromospheric and TR structures do not reach coronal heights.

But there must be a “classic” TR to coronal structures. And some dynamic chromospheric phenomenon may feed the corona.

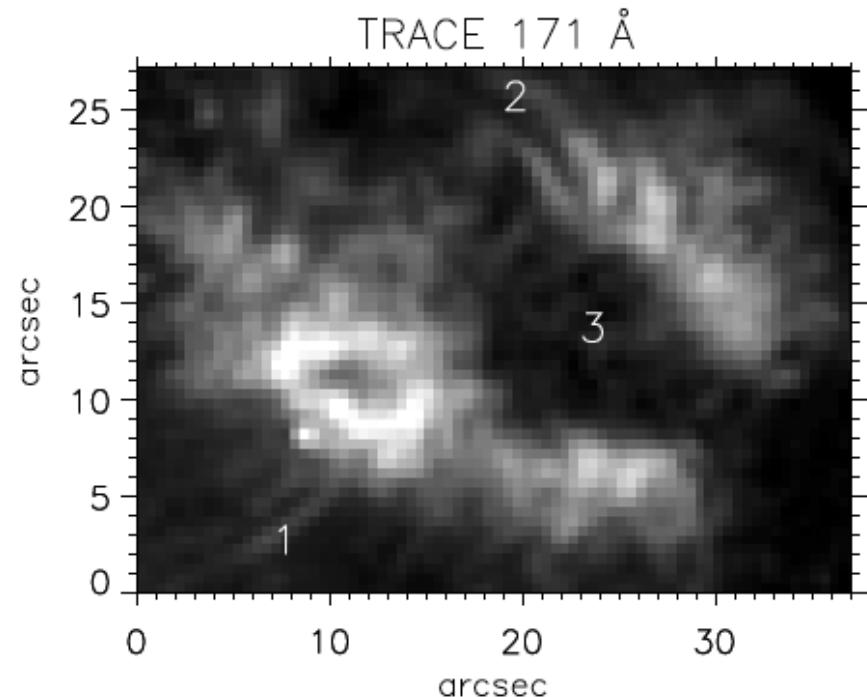
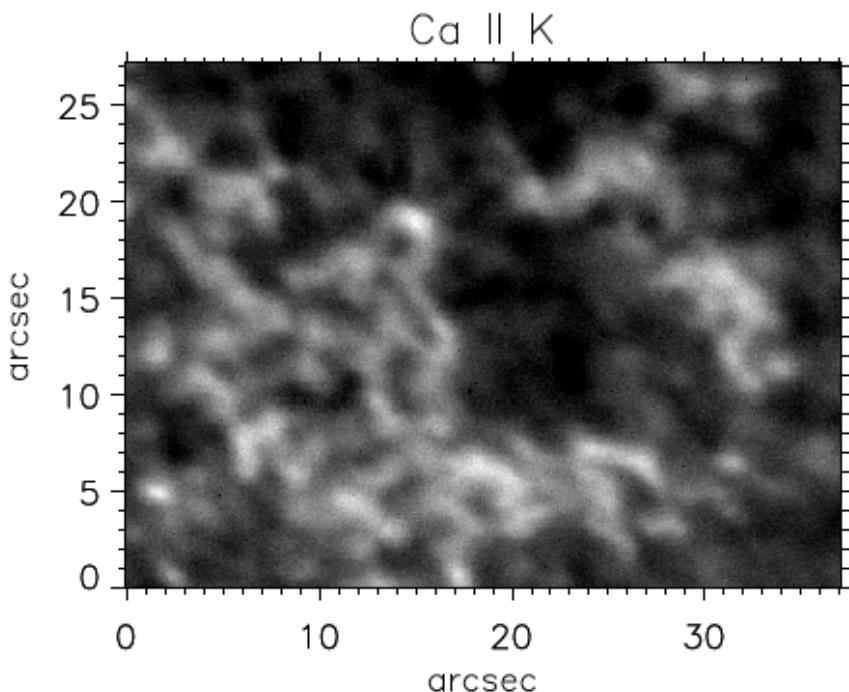
Hi-C II will look for the chromospheric-coronal connection in the two most obvious places, Type II spicules and hot core loops.

Hi-C II – Exploring the Chromospheric-Coronal Connection



Do Type II spicules result in coronal plasma?

Hi-C II – Exploring the Chromospheric-Coronal Connection

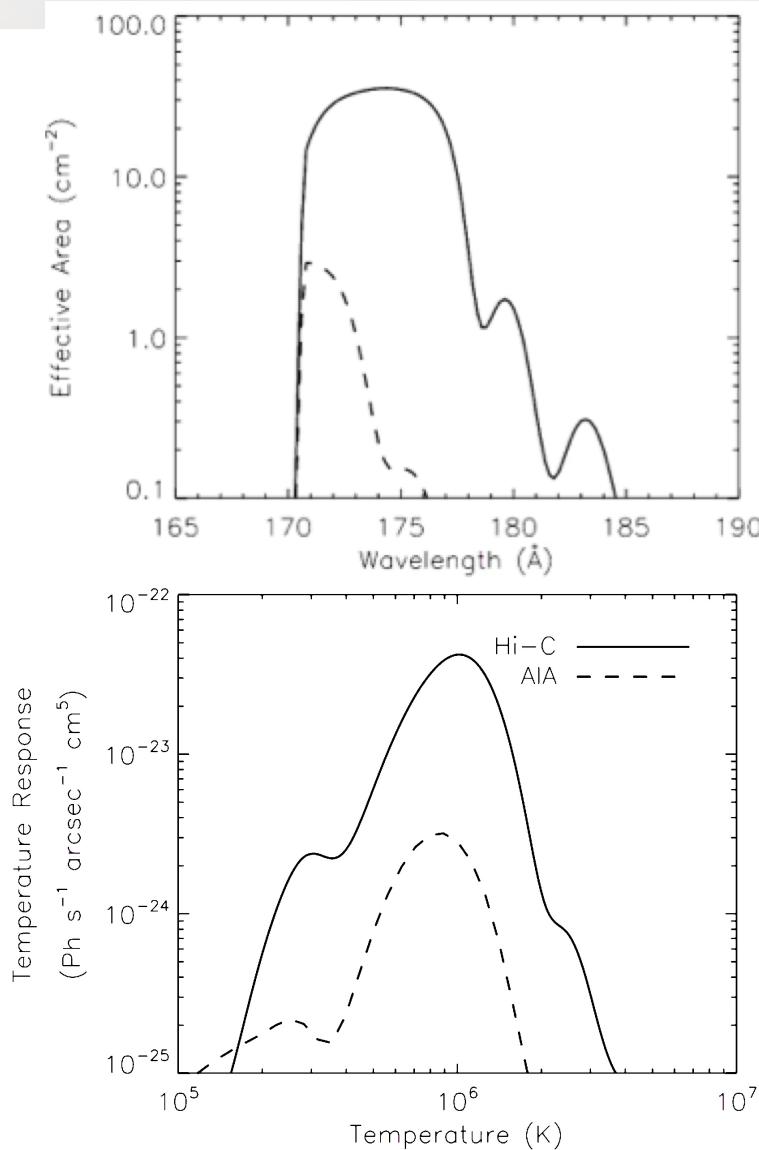


Can moss elements be traced through various TR temperatures?

De Pontieu et al, 2003

Hi-C II

- Telescope design capable of $\sim 0.25''$ resolution at the solar corona,
- Multi-layer coatings for EUV observations in the 171Å passband,
- High sensitivity to EUV flux sufficient for a 5 s cadence,
- Pointing stability necessary to achieve resolution goal,
- Image readout and data storage capable of maintaining high-cadence observations, and
- Camera with low readout noise.
 - Camera for Flight #2 will feature an e2V 2Kx2K CCD with 12um pixels
 - Using very similar board layout and electronics design as CLASP, HiC camera read noise expected not to exceed $8 \text{ e}^{-1}/\text{pixel}$



Sounding Rocket Instruments at MSFC

